

EVALUATING MODELS OF WORKING MEMORY:
FMRI AND BEHAVIORAL EVIDENCE ON THE
EFFECTS OF CONCURRENT IRRELEVANT INFORMATION

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FMRI and behavioral methods were used to examine working memory impairments resulting from articulatory suppression, irrelevant speech, and irrelevant nonspeech. While the deleterious effects of these three irrelevant information types are well established in the behavioral literature, theoretical models provide conflicting accounts of the origins of these effects. To adjudicate between these accounts, two experiments were conducted. Experiment 1 examined fMRI signal changes in a delayed probed recall task with articulatory suppression, irrelevant speech, or irrelevant nonspeech imposed during the encoding and delay periods. Within the principally frontal and left-lateralized network of brain regions engaged by the task, articulatory suppression caused a relative increase in activity early in the trial, while both irrelevant speech and nonspeech conditions caused relative reductions in regional activity later in the trial. In a subsequent behavioral experiment (Experiment 2), the specific timing of interference was manipulated to further explore apparent differences in the temporal specificity of the effects. Subjects performed a delayed serial recall task while irrelevant information was imposed during specific trial stages: encoding, delay, or recall. Articulatory suppression was found to be most effectual when it coincided with item encoding, while both irrelevant speech and irrelevant nonspeech were most effectual when presented during the post-presentation delay. Taken together, these experiments provide convergent evidence for a dissociation of articulatory suppression from the two irrelevant sound conditions, but suggest that the effects of irrelevant speech and irrelevant nonspeech are functionally equivalent. This pattern of dissociation is predicted by the Embedded-Processes model (Cowan, 1995), but proves challenging to explain in the context of alternative theories.

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I.

INTRODUCTION

Since the cognitive revolution of the mid 1950's, short-term memory has been, and continues to be, one of the most actively researched topics in cognitive psychology (e.g., Eysenck & Keane, 1995). Early research on short-term memory focused on the role of temporary maintenance processes in the performance of simple memory tasks, like remembering a phone number or a list of grocery items. As the characteristics of short-term maintenance came to be better understood, so did its more expansive role in supporting “higher” cognitive abilities, such as learning and comprehending language (Gathercole & Baddeley, 1993; Just & Carpenter, 1992), reasoning and solving problems (Logie, Baddeley, Mane, Donchin, & et al., 1989; Salthouse, 1992), and even thinking (Jonides, 1995; Logie & Gilhooly, 1998). In recognition of its centrality to these higher cognitive functions, many modern cognitive theorists have come to favor the term *working memory*, which emphasizes the active processing, monitoring, and manipulation of short-term memories that must take place to support ongoing cognition.

A great deal has been learned about working memory – its limitations, factors that influence its precision, the range of cognitive functions for which it is essential, and most recently, its neural correlates – yet the specific nature of the mechanisms and representations that underlie working memory remain hotly contested. While Alan Baddeley's multiple-component model has been perhaps the most influential, several alternative models prove capable of explaining a similar body of evidence despite taking rather diverse theoretical positions

(Gathercole, 1996; Miyake & Shah, 1999; Richardson, Engle, Hasher, Logie, & et al., 1996).

Perhaps the greatest opportunity to adjudicate between these competing models is presented in cases where they yield conflicting empirical predictions. One such case, regarding the disruptive effects of irrelevant information on working memory performance, has become the topic of an active debate in the cognitive literature (Baddeley & Larsen, 2003; Baddeley, 2000; Hanley & Bakopoulou, 2003; Jones & Tremblay, 2000; Larsen & Baddeley, 2003; Larsen, Baddeley, & Andrade, 2000; Macken & Jones, 2003; Neath, 2000; Neath, Farley, & Surprenant, 2003; Neath & Surprenant, 2001; Page & Norris, 2003). This debate forms the foundation for the present work, which introduces novel empirical evidence based on the neuroanatomical and temporal specificity of irrelevant information effects, and applies the evidence to evaluate four working memory theories that have been previously argued to account for the effects: The Phonological Loop (Baddeley, 1986; Larsen & Baddeley, 2003; Salamé & Baddeley, 1982), the Object-Oriented Episodic Record (Jones, Beaman, & Macken, 1996), Feature Model (Nairne, 1990; Neath, 2000), and the Embedded-Processes Model (Cowan, 1995, 1999).

Three types of irrelevant information that disrupt working memory are most pertinent to the debate, and thus the present work: 1) irrelevant articulations produced by the subject, referred to as *articulatory suppression*, 2) background *irrelevant speech* produced by a source other than the subject, and 3) background *irrelevant nonspeech*, also from by a source other than the subject. The specific explanation for the disruptive effects of each type of irrelevant information differs considerably from theory to theory. Most importantly for the present work, alternative theories make conflicting claims about the functional equivalence of the three irrelevant information effects. That is, the models disagree on whether a given type of information affects memory in the same way, or in a different way, than does another type of information (see

Figure 1a). These distinct patterns of functional equivalence/distinction yield different patterns of prediction from each theoretical model that are exploited in the two experiments that comprise this paper. In Experiment 1, functional magnetic resonance imaging (fMRI) is used to investigate the patterns of dissociation revealed in the neuroanatomical and temporal specificity of each irrelevant information effect. In Experiment 2, the temporal specificity of each effect is further examined through a novel behavioral approach suggested by the imaging data from Experiment 1, and by meta-analysis of the extant behavioral literature, in which irrelevant information is presented during temporally limited stages of working memory performance.

The Effects of Irrelevant Information on Working Memory

In order to appreciate the differing accounts provided by alternative theories, it is necessary to first understand the specific nature of the three irrelevant information effects and the factors that influence their magnitude and reliability.

Articulatory Suppression

The *articulatory suppression effect* can be defined as a reduction in WM span associated with a dual-task condition in which subjects are required to repeat an irrelevant verbal token (e.g., “the, the, the, ...”) during working memory task performance. The impact of articulatory suppression (also referred to as concurrent articulation) on working memory was observed initially by Murray (Murray, 1968), who found that requiring subjects to vocalize something other than presented items (e.g., another letter, or the word “the”) caused a substantial decrement to recall performance. The disruption produced by concurrent articulation has since been generalized along a number of dimensions. Notably, similar impairments are observed even when the irrelevant vocalizations are asynchronous with the TBR stimuli, indicating that the effect is not simply one of perceptual or attentional masking (Baddeley, 1986). Moreover, significant

articulatory suppression effects are found to persist regardless of whether the items are repeated overtly or covertly, though the effect does seem to be larger for overt repetition (Gathercole, 1986; Gupta & MacWhinney, 1995; Macken & Jones, 1995). The effect also seems to be somewhat insensitive to the particular item or items uttered (Baddeley, 1990). For example, repetition of a single word (e.g., ‘the’, ‘blank’, ‘double’, ‘hiya’), multisyllabic nonword (‘kwelstry’, Gupta & MacWhinney, 1995), and counting in sequence (e.g., ‘one, two, three’, Longoni, Richardson, & Aiello, 1993) have all been shown to produce sizable suppression effects. There is some evidence, however, that articulation of changing-state (time-varying) sequences has the most substantial effect on serial recall performance (Macken & Jones, 1995). While articulatory suppression has been studied most frequently in the context of serial recall paradigms, suppression effects have also been observed in non-serial verbal recognition (e.g., Murray, Rowan, & Smith, 1988).

Irrelevant Speech

The effect of irrelevant background speech (also called unattended speech) is equally well established, though it tends to be smaller in size than that of articulatory suppression (Neath, Surprenant, & LeCompte, 1998; Salamé & Baddeley, 1982). The effect can be defined as a reduction in WM span that arises from the auditory presentation of varying background speech information during working memory task performance. While early attempts to examine the impact of background sounds on short-term memory using white (Gaussian) noise showed no associated impairment (Hintzman, 1965; Murray, 1965), Colle and Welsh (1976) demonstrated that background speech, even in a language unfamiliar to participants, produces a substantial degradation of working memory. Once again, the generality of this effect has been verified in a vast number of more recent studies. As with articulatory suppression, it is quite clear that

irrelevant speech effects do not derive from simple perceptual masking or by preventing registration into memory. For example, a series of experiments conducted by Salamé & Baddeley (1986) showed that several non-mnemonic tasks (e.g., case judgment, homophony judgment) are unimpaired by irrelevant speech, suggesting that the stimuli can be accurately perceived despite the background noise. Moreover, the intensity of the background speech appears to have no influence on the size of the effect for visually presented items, with intensities ranging from a whisper (48dB) to a shout (95dB) producing approximately equivalent effects (Colle, 1980; Jones, Alford, Bridges, Tremblay, & Macken, 1999; Salamé & Baddeley, 1987; c.f. Stevenson, 2002). Perhaps most convincingly, Miles, Madden, & Jones (1991) have demonstrated that strong irrelevant speech effects are obtained even when the sounds occur only during a retention period following item presentation. The irrelevant speech effect also appears not to habituate over time. That is, most studies indicate that its strength is not attenuated over repeated trials (Jones & Macken, 1995a; Tremblay & Jones, 1998), though two studies (Banbury & Berry, 1997; Morris & Jones, 1990) have found that the effect is dampened after 20 minutes of pre-exposure to the irrelevant sequence.

While most typically observed in tasks that demand maintenance of serial order, there is mixed evidence about generalization of the irrelevant speech effect into non-serial tasks. Results from Baddeley & Salamé (free recall task 1990) and Beaman & Jones (1997, missing item task; 1998, (free recall, 1998) suggest that irrelevant speech impairs performance only when subjects must maintain item order. However, LeCompte has observed significant irrelevant speech effects in free recall, forced choice recognition, and missing item tasks (LeCompte, 1994, 1996). Tremblay & Jones (2000) (2000) suggest that the apparent discrepancy can be reconciled if one assumes that even “non-serial” tasks show the effect provided that subjects employ a serial

rehearsal strategy. This account has difficulty with the findings of Surprenant et al. (1999), however, in which a significant irrelevant speech effect was obtained in an 80 word recognition task for which serial rehearsal seems an unlikely maintenance strategy.

Although the effect appears to be quite robust, a number of factors do seem to influence its magnitude. One issue of theoretical importance is whether the specific phonological content of the irrelevant speech is a determinant of the size of the effect. In the early work of Salamé and Baddeley (1982, Experiment 5), the authors found that phonological overlap between the irrelevant speech stream and the TBR items was a critical factor. However, numerous studies have since been published in which such between-stream similarity was found to be unimportant to the effect (Bridges & Jones, 1996; Jones & Macken, 1995b; Larsen et al., 2000; LeCompte & Shaibe, 1997). These repeated failures to replicate Salamé & Baddeley's original findings have nearly put the issue to rest. However, a recent study published by Tolan & Tehan (2002), reporting significantly increased errors due to between-stream similarity in a cued-recall proactive interference paradigm intimates that there may indeed be feature interactions across the memorial and irrelevant information.

A somewhat more reliable observation in irrelevant speech is the importance of changing-state. It has been widely shown that irrelevant sound sequences that vary with time are considerably more disruptive than steady-state sequences lacking this variation (Campbell, Beaman, & Berry, 2002; Jones et al., 1999; Jones, 1994; Jones, Madden, & Miles, 1992; LeCompte, 1995; Tremblay & Jones, 1998). Two corollaries to the changing-state observation are the effects of word-dose (Bridges & Jones, 1996) and token-set-size (Tremblay & Jones, 1998). Specifically, the more items that are encountered in a changing-state speech sequence, either because they arrive more rapidly or for a longer period of time (dose), or because they are

sampled from a larger pool (token-set), the larger the effect. An interesting caveat to these findings, however, is that it may be possible to vary an irrelevant sound sequence by too great a degree, at which point it will have a less disruptive effect (Jones et al., 1999).

Irrelevant Nonspeech

The irrelevant nonspeech effect can be defined as a reduction in WM span that results from the presentation of a background acoustic stream containing varying sounds not perceived as speech by the subject during working memory task performance. As mentioned above, it has long been known that white-noise, which is perceived as a nonspeech steady-state sound, does not impair working memory performance. However, Salamé & Baddeley (1989) observed a modest (and somewhat unexpected) deleterious effect of instrumental music (that was devoid of any speech content). Jones and Macken (1993) interpreted this finding as an indication that, like speech, nonspeech sounds could influence working memory provided that they comprise changing-state information. To test this hypothesis, a series of experiments were conducted using sine-wave tones of changing pitch as the irrelevant nonspeech stimuli. The results were clear, showing that time-varying but not repeated tones significantly interfered with working memory performance. Moreover, the effect of tones was found to be as substantial as that of a changing-state speech utterance (Jones & Macken, 1993, Experiment 5). The effect of changing-state irrelevant nonspeech has since been replicated several times with tones (Jones et al., 1999; LeCompte, Neely, & Wilson, 1997; Neath & Surprenant, 2001; Tremblay & Jones, 1998)¹ and with a wide range of other nonspeech stimuli (sharply varying music, Klatte, Kilcher, & Hellbrueck, 1995; animal sounds, Neath & Surprenant, 2001; broadband noise, Tremblay, Macken, & Jones, 2001).

Whether these nonspeech effects should be equated with those obtained for speech, however, remains an issue of debate. Like irrelevant speech, irrelevant nonspeech effects are dependent on changing-state and become more substantial with increases in token-set-size (Tremblay & Jones, 1998). In addition nonspeech seems to produce the same impact on serial-spatial tasks as does speech (Jones et al., 1999). However, the magnitude of impairments due to irrelevant nonspeech is frequently smaller than that found with speech (LeCompte et al., 1997; Tremblay & Jones, 1998).

Four Theories, Four Competing Accounts

On the basis of selective aspects of the empirical evidence, explanations for the effects of articulatory suppression, irrelevant speech, and irrelevant nonspeech have been constructed in the context of four alternative theories of working memory. While each of these distinct accounts is detailed below, it should be emphasized at the outset that for the purposes of the present paper it is somewhat unimportant how the explanation of a given effect varies across models. What is rather more important, is that the models differ in their assumptions about the shared versus distinct sources of each effect.

The Phonological Loop

It is largely through the seminal work of Baddeley and his colleagues that short-term memory has come to be viewed not as a passive repository, but as an active, *working* memory. The multiple-component model that has emerged through his work posits a dedicated short-term memory system (i.e., dissociable from long-term memory) in which temporal decay is the primary source of limitation. The structure of the model is depicted in Figure 1b. The model

¹ In initial pilot work associated with the present study, a significant effect of irrelevant tones proved difficult to obtain, though additional factors such as the absence of a delay period may have confounded the attempt.

asserts that there are separate systems responsible for the maintenance of distinct types of information; one subsystem specialized for maintaining verbal (linguistic, speech-like) material, the *phonological loop*, and a second subsystem specialized for maintaining nonverbal (spatial, form-based) material, the *visuospatial sketchpad*. In addition, Baddeley (e.g., Baddeley & Hitch, 1974) posits a separate attentional controller, *the central executive*, which guides the behavior of the maintenance subsystems, provides them with additional processing capacity, and supports the monitoring and manipulation of information in working memory.

The phonological loop is most relevant to the explanation of irrelevant information effects, and is thought to be further divided into two subcomponents, a passive *phonological store* that retains verbal information as a set of phonological representations (each subject to decay), and an active *rehearsal process* that refreshes these representations in a manner akin to subvocalization or “inner speech.” Rehearsal is assumed to be a strategic way to retain information over durations that exceed the temporal decay limits of the store. Rehearsal is also thought to allow recoding of visually presented verbal information into a form suitable for storage, whereas auditory-verbal information is assumed to have direct access to the phonological store.

Under the phonological loop hypothesis, articulatory suppression is thought to have two disruptive consequences for working memory, both a byproduct of preventing the active rehearsal process. First, articulatory suppression is thought to engage the rehearsal mechanism during encoding, and to thus obstruct the conversion process allowing visually presented information to be registered into the phonological store. Second, by taxing the speech apparatus that supports subvocal rehearsal, articulatory suppression prevents decaying memoranda from being refreshed.

By contrast, the phonological loop account consigns irrelevant speech effects to the phonological store, rather than rehearsal process. Based on the work of Salamé & Baddeley (P. Salamé & A. Baddeley, 1990; Salamé & Baddeley, 1982, 1986), it was initially proposed that irrelevant speech, by virtue of its phonological content, would gain obligatory access to the store. As a consequence, interference would be produced by interactions between the irrelevant items and the memorial representations residing in storage. Entry to the store was assumed to be filtered such that only phonological (speech-like) information could pass, thus explaining the null effects of noise on memory (Salamé & Baddeley, 1989). While the specific mechanism by which corruption of memory occurred was not detailed, a logical prediction derived from this explanation was that larger irrelevant speech effects would be produced when the phonemes in the irrelevant stream overlapped with those in the TBR items (Baddeley, 1992; Salamé & Baddeley, 1989). This original formulation of the phonological loop account is frequently used to evaluate the ability of the model to address irrelevant speech findings (e.g., Hanley, 1997; Neath & Surprenant, 2001). However, in light of more contemporary evidence that the between-stream similarity effect is not reliable, Baddeley and colleagues (Baddeley, 2000; Larsen & Baddeley, 2003; Norris, Page, & Baddeley, in press) have very recently revised their position. Importantly, this revised view still attributes irrelevant speech effects to processes taking place in the phonological store (Larsen & Baddeley, 2003, p. 1262). However, it no longer maintains that there is corruption of the item representations themselves, and instead, irrelevant speech is proposed to add “noise” to the representation of order information in memory.

The original formulation of Salamé & Baddeley quite clearly placed irrelevant nonspeech effects in a different locus than irrelevant speech effects, since only speech could pass into the phonological store and only speech could cause corruption by virtue of phonemic

overlap with the memorial representations. While the revised account is somewhat ambiguous with respect to irrelevant nonspeech, the continued assumption that irrelevant speech effects take place in a storage medium devoted specifically to “phonological” representations almost forces the conclusion that nonspeech effects must have an alternative origin. Baddeley has not explicitly acknowledged this conclusion, but tacit acceptance is suggested by the lack of a refutation in his response to Neath (2000), wherein it was suggested that dual-task interference occurring in the central executive provides the best explanation of irrelevant nonspeech effects in the context of the phonological loop model (Baddeley, 2000).

The O-OER Model (Changing State Hypothesis)

Jones and his colleagues (e.g., Jones et al., 1996; Jones, Macken, & Murray, 1993) have proposed a very different view of working memory in the Object-Oriented Episodic Record (O-OER) model (Figure 1c). Unlike Baddeley’s model, which assumes that there are separate stores dedicated to the maintenance of different types of information, the O-OER model assumes that temporary storage takes place on a unitary virtual surface wherein all events are represented as amodal, abstract *objects*. For auditory stimuli, objects in short-term memory are created automatically by the psychophysical processes that detect boundaries in auditory perception (see e.g., Bregman, 1990). That is, unique objects are established whenever there is a sufficient change in the energy of incoming information as to signal the arrival of a distinct event (and thus give rise to a discrete perception) – this is the *changing-state hypothesis* (e.g., Jones et al., 1993). Temporally successive events are thought to be chained together into streams of ordered objects connected by *episodic pointers*. In contrast to the automatic “streaming” of auditory stimuli, the establishment of episodic pointers between successive visual items is presumed to occur via covert articulatory mechanisms (Jones et al., 1993; Macken & Jones, 1995). However, the

underlying objects created by any event are abstract and indistinguishable with respect to their origin (amodal). The strength of the episodic pointers between objects is also dependent on several factors, including the ease of segmentation and the number of times the stream has been traversed (e.g., via non-articulatory rehearsal, see below). Importantly, once established, the object representations themselves are assumed not to degrade with time. Instead, the model assumes that it is the links between objects (the episodic pointers) that are subject to temporal decay, but can be refreshed via rehearsal.

In the O-OER model, both the rehearsal and the retrieval of objects in short-term memory is based on a “threading” process, whereby each object in a stream is sequentially activated and the links between them “revivified” (Jones & Macken, 1995a). Accordingly, the ability to recall a set of items is dependent on the maintained integrity of the links between them. Moreover, the ability to correctly navigate a stream of connected objects (both during rehearsal and retrieval) is thought to be hindered by the presence of other sets of pointers (i.e., other streams associated with a different source) in memory. While the specific relationship between articulation and rehearsal is somewhat ambiguous in the model, the description provided by Macken & Jones (1995) asserts the position that while subjects normally articulate (overtly or covertly) items as they traverse a stream, such traversal can also be conducted in the absence of articulation. That is, “rehearsal only involves the activation of successive objects, as opposed to articulation of them” (Macken & Jones, 1995, p. 447).

Accordingly, the O-OER model does not explain articulatory suppression effects as a disruption of the rehearsal process. Instead, irrelevant articulations are thought to give rise to their own object representations in memory. Provided that there is sufficient variation in the articulated sequence, then episodic pointers will be established between the objects. The basic

claim of the O-OER model is that the instantiation of new links between the irrelevant objects produced by articulation causes a disruption of the serial traversal of TBR items, leading to incorrect or missing pointers between memorial objects. Since the objects themselves carry no information about the stream to which they belong, recollection is subsequently significantly impaired.

Precisely the same account is provided to explain the effects of irrelevant speech and nonspeech. That is, changing-state irrelevant sounds of any type are assumed to be automatically registered into memory by the segmental processes of auditory perception. The links that represent order in these irrelevant streams compete with those established between the TBR, and disruption of memory for the presented items ensues. As evidence of this equivalence for speech and nonspeech, Jones and colleagues site the extension of the irrelevant sound phenomenon to sounds as devoid of phonological content as sine tones (Jones & Macken, 1993) and bursts of broad-band noise whose center frequency changes from burst to burst (Tremblay et al., 2001), as well as the observation that changing-state is the essential determinant of the size of the effect for both speech and nonspeech (e.g., Jones & Macken, 1993; Tremblay & Jones, 1998). The authors of this view further emphasize that based on the O-OER account, it is the similarity of process (seriation), not similarity of content (overlap of features present in the irrelevant and TBR streams) that causes the disruption. Thus, the absence of between-stream similarity effects is completely expected.

The Feature Model

Nairne, Neath, and their colleagues (Nairne, 1990; Nairne, 2001; Neath, 2000; Neath & Nairne, 1995) have forwarded still a different view of the machinery underlying performance of working memory tasks, and have embodied their view in the Feature model (see Figure 1d). The

Feature Model may be differentiated from the two previously considered theories in at least the following ways: 1) working memory task performance arises specifically through the interactions between the short-term (*primary*) and long-term (*secondary*) memory systems, 2) information is retrieved from secondary memory storage via temporarily maintained cues (kept in primary memory), and not by direct access to information retained in an accessible “activated” form, 3) rehearsal, and other covert reactivation processes, play a very limited role in mediating performance, and 4) memory degradation occurs through interference between memory traces, not through temporal decay.

The Feature model takes its name from the use of vectors of elements as a way to characterize information in memory, wherein each element of the vector represents some “feature” of stored information (see also Hintzman, 1991). Two feature types are assumed to comprise a memory trace, *modality-dependent* features that encode an item’s physical characteristics, and *modality-independent* features that encode an item’s internally generated representations. Auditory stimuli are assumed to possess considerably more modality-dependent features than do visual stimuli (while both are equated with respect to modality-independent features). Whenever a memory trace is formed, it is encoded simultaneously into two separate memory systems, *primary memory* and *secondary memory*, each having different properties. While secondary memory traces remain veridical (i.e. do not degrade), the traces encoded into primary memory are subject to interference from the encoding of subsequent items, and from the by-products (other traces) of ongoing cognitive processes operating independently from those responsible for item representation. However, only the primary memory traces are available to conscious awareness. The primary memory system can therefore be thought of as “a repository of cues” (Nairne, 2002, p. 286), responsible for maintaining feature traces that are not themselves

recallable, but permit access to the intact traces preserved in secondary memory. The success of this retrieval process is dependent on how the available cues (in primary memory) match unique traces in secondary memory.

The Feature model accordingly offers a unique framework in which to interpret the three irrelevant information effects. Articulatory suppression is thought to disrupt memory by overwriting the features contained in to-be-remembered item traces (Nairne, 1990). This overwriting is implemented computationally through a process of “feature-adoption,” in which memorial item features are substituted with features of the irrelevant utterance (i.e., the memorial traces “adopt” features of the utterance). Since the irrelevant traces produced during concurrent articulation are internally generated and thus devoid of modality-dependent features, it is assumed that only modality-independent features could be affected by feature-adoption.

Although the earliest version of the model was not designed to explain irrelevant speech effects, Neath (2000) developed an extension explicitly for this purpose. Motivated by empirical observations suggesting that irrelevant speech behaves just like articulatory suppression in how it interacts with other effects (see discussion above), the extended model assumes that irrelevant speech effects emerge from the same feature-adoption process as is used to explain articulatory suppression effects. Accordingly, just as novel traces produced by articulatory suppression are thought to corrupt modality-independent features in the memory trace, so are the novel traces produced by irrelevant speech. However, to account for the relatively increased magnitude of articulatory suppression effects, Neath (2000) assumes that additional executive resources (modeled as a single scaling parameter) are deployed under suppression due to the extra burden of producing utterances, as compared to passively listening to them.

While articulatory suppression and irrelevant speech are treated similarly by the Feature Model, irrelevant nonspeech effects must be explained by other means. Specifically, the process of feature-adoption is not readily extended to irrelevant nonspeech since the modality-independent features produced for nonspeech traces would be unlikely to interact with those produced to represent speech tokens (Neath, 2000). Consequently, irrelevant nonspeech effects are argued to be better conceived as the result of the dual-task context they create – one task requiring subjects to maintain the TBR items, and the other requiring them to ignore irrelevant sounds (Neath, 2000; Neath & Surprenant, 2001).

The Embedded-Processes Model

While proponents of the previously discussed theories have participated most actively in the debate, a fourth viable position is conferred by a controlled attention view of working memory (Cowan, 1999; Engle, 2002; Schneider & Chein, 2003; Schneider & Detweiler, 1987). Although it is likely that similar accounts could be constructed in the context of other attentional models of working memory, the additional perspective on irrelevant information effects has typically been attributed to Cowan's Embedded-Processes model (on the basis on discussion presented in Cowan, 1995). Following the tradition of Broadbent (1958) and Norman (1969), the main intent of the Embedded-Processes model is to account for a wide range of empirical findings in the fields of attention and working memory within one common framework. Though Cowan has at times likened his view to Baddeley's (Cowan, 1993), there are several fundamental distinctions: 1) working memory is viewed as a subset of long term memory, rather than as a dedicated temporary storage system, 2) short-term memory for distinct types of stimuli (e.g., verbal, visuospatial) occurs within a common storage medium (LTM), not in material specific

maintenance subsystems, and 3) strategic processes other than subvocal rehearsal are thought to play a significant role in reactivating stored information.

The basic structural elements of the Embedded-Processes model are shown in Figure 1e. In the model, there is only one memory repository,² which represents all information as a set of features (or feature combinations). This single store is equated with the long-term memory system. However, information in this system can be made more readily accessible, or brought into working memory. Entry into working memory occurs as an “embedded” subset of information in the long-term store is given a temporarily heightened state of activation. This activation is time limited and subject to decay. A further embedded subset of the activated information can be made particularly salient by entering into the *focus of attention*. The focus of attention, however, is capacity limited and can cover only a small amount of information at any one time (the capacity is estimated to be four representational units, Cowan, 2001). Working memory is assumed to comprise all information in a readily accessible state by virtue of its activation, including information within the focus of attention, as well as information in an activated state outside of attention (Cowan, 1995).

As in Baddeley’s framework, the Embedded-Processes model assumes a central controller that provides domain-general processing capacity. Among other functions, this controller supervises covert processes that serve to maintain information over time (e.g., to reactivate decaying activity). While the model treats subvocal rehearsal as one such reactivating mechanism, it emphasizes that searching through a set of memory items by iteratively subjecting them to the focus of attention can also serve this function (Cowan, 1992, 1999). Cowan and his colleagues have likened this reactivating search process to Sternberg’s (1966; 1975) notion of

fast memory scanning, and this alternative covert reactivation strategy will hereafter be referred to as *attentional scanning*. While this process is arguably dissociable from subvocal rehearsal (e.g., Clifton & Tash, 1973; Cowan et al., 1998), Cowan (2001) notes that the same attentional mechanisms used in attentional scanning may also be employed to establish a rehearsal sequence.

While handling of the articulatory suppression effect in the Embedded-Processes model is somewhat nebulous, Cowan's descriptions most strongly suggest a view analogous to that offered by the Phonological Loop hypothesis. Namely, that articulatory suppression effects are derived from disruption of the speech-processing system used to subvocally rehearse items (Cowan, 1995, 2001). An alternative position is also allowed by the model, however, wherein the common attributes of the irrelevant utterance and memorial items produce mutual interference in active memory (as in the Feature model). While discussion of articulatory suppression within this framework does not definitively rule out a third possibility that suppression has its effect by disrupting the attentional scanning mechanism, Cowan (2001, p. 99) seems to reject this position on the grounds that it can't explain why suppression fails to impair performance when a large pool of words is used to construct TBR lists (la Pointe & Engle, 1990).

In contrast, Cowan (1995) is clear that both irrelevant speech and nonspeech effects are assumed to have an attentional origin. Specifically, he has put forward the view that the deleterious influence of irrelevant sound on working memory arises from the diversion of the focus of attention away from TBR item representations during attentional scanning. This diversion is likened to the orienting response (Sokolov, 1963), wherein a novel, unexpected, or

² Cowan's model does include a very brief sensory store in addition to the long-term memory store. This aspect of the model is not addressed in the present paper.

salient stimulus elicits an automatic attentional reaction. Similarly, novel components of the irrelevant sound stream are thought to interfere with attentional scanning by demanding momentary attentional processing (a sort of “attentional blink”). A very compelling aspect of this hypothesis is that like the orienting response, the effects of irrelevant sound (speech and nonspeech) have proven to be highly dependent on the presence of novel, or changing-state, features in the irrelevant sound stream. This finding further denies the same explanation as an account for the articulatory suppression effect, in that it is robust even with highly repetitive (i.e. “steady-state”) utterances. Moreover, it seems intuitively unlikely that information produced intentionally by the subject would trigger an orienting response.

Adjudicating Between Alternative Theories on the Basis of Effect Interactions

As can be seen, the four models discussed above each address the effects of irrelevant information in a unique way, and accordingly, provide unique predictions regarding their specific influence on working memory processing. To date, evidence on the interactions of articulatory suppression, irrelevant speech, and irrelevant nonspeech with other factors known to influence working memory, and with each other, has served as the primary basis for evaluating these alternative theoretical claims. For example, several theoretical assumptions rest on the presumed interactions between the irrelevant information effects, and the effects of word-length and phonological similarity. These latter phenomena are characterized by reductions in working memory span when the TBR items are either long in articulatory duration (word-length, Baddeley, Thomson, & Buchanan, 1975) or have partially overlapping sounds (phonological similarity, Conrad & Hull, 1964).

Though dependent on the modality of presentation, there is apparent consensus regarding the interactions between articulatory suppression and word-length, and between articulatory

suppression and phonological similarity. In the visual modality, articulatory suppression removes both the word-length effect (Baddeley et al., 1975) and the phonological similarity effect (Baddeley, Lewis, & Vallar, 1984). In the auditory modality, however, suppression eliminates only the word-length effect, and *not* the phonological similarity effect (Baddeley et al., 1984; Longoni et al., 1993; Peterson & Johnson, 1971). These findings are the primary justification for dissociating phonological storage and subvocal rehearsal in the Phonological Loop model, and for consigning articulatory suppression effects to the latter (rehearsal) system (see e.g., Baddeley et al., 1984). However, Neath and colleagues have argued that irrelevant speech shows precisely the same pattern of interaction with word-length and phonological similarity, and thus challenge Baddeley's assumption that articulatory suppression and irrelevant speech effects have distinct sources. Specifically, Neath and colleagues find that just like articulatory suppression, irrelevant speech eliminates both the word-length (Neath & Surprenant, 2001, Experiments 2 & 3; Neath et al., 1998) and phonological similarity (Colle & Welsh, 1976; Neath & Surprenant, 2001, Experiment 1) effects with visual presentation, but only the word-length effect (Neath et al., 1998) and not the phonological similarity effect (Surprenant et al., 1999) with auditory presentation. This apparent correspondence between articulatory suppression and irrelevant speech is the basis for ascribing functional equivalence to these effects in the Feature model. Meanwhile, the position of the Feature model that irrelevant nonspeech must have a unique origin gains support from evidence that, unlike articulatory suppression and irrelevant speech, irrelevant nonspeech fails to eliminate either the phonological similarity effect (Neath & Surprenant, 2001, Experiment 1) or the word-length effect (Neath & Surprenant, 2001, Experiments 2 & 3; Neath et al., 1998) with visual presentation.

The reliability and methodological validity of these studies have been questioned, however, by both Baddeley and colleagues (Baddeley, 2000; Larsen & Baddeley, 2003; Larsen et al., 2000) and Jones and colleagues (Tremblay et al., 2000). Baddeley (2000) argues that the length of TBR lists employed by Neath and colleagues (8 items) exceeds the normal capacity of phonological working memory, and thus forces the deployment of atypical maintenance strategies. Indeed, several studies conducted in Baddeley's lab (Larsen & Baddeley, 2003; Larsen et al., 2000; Salamé & Baddeley, 1986) report that the phonological similarity effect subsists under irrelevant speech when visual presentation is combined with lists having fewer than eight items. These findings appear to contradict those obtained by Neath & colleagues. Meanwhile, Jones and colleagues (Jones, Alford, Macken, Banbury, & Tremblay, 2000; Tremblay et al., 2000) report that they are unable to replicate aspects of Neath's results, and find instead that word-length effects also continue to be manifest under irrelevant speech with visually presented items. Thus, while the number of TBR items in the tested lists may explain the inconsistency, a consensus characterization of the interactions between irrelevant speech and other factors has yet to emerge.

Perhaps the most critical evidence for, or against, the functional equivalence of the three irrelevant information effects could be derived from studies examining their interaction with one another (e.g., the interaction between articulatory suppression and irrelevant speech effects). That is, a seemingly viable approach to evaluating the alternative claims is to assert that two effects deriving from distinct functional sources should produce additive impairments in working memory, whereas effects having a common source should produce redundant consequences, and thus be under-additive (or masked). Indeed, several studies have taken this approach toward evaluating the theoretical claims (e.g., Hanley & Bakopoulou, 2003). It can be argued, however,

that even the basic logic of these experiments breaks down in some models [see for example Salamé & Baddeley's (1986) account of the super-additivity of phonological similarity and irrelevant speech, both thought to have the same locus]. Even more problematic is that the literature on interactions between articulatory suppression and irrelevant sound effects is muddled by inconsistencies.

When items are presented visually, the most frequent finding is that articulatory suppression eliminates the irrelevant speech effect (Hanley, 1997; Salamé & Baddeley, 1987; Salamé & Baddeley, 1982). However, an experiment by Macken & Jones (1995, Experiment 5) found that mouthed changing-state suppression reduces, but does not eliminate the effect of irrelevant speech. The results with auditory presentation are even more inconsistent. An early study conducted by Hanley & Broadbent (1987) produced mixed results, with one experiment showing an elimination of the irrelevant speech effect under articulatory suppression (Experiment 1), but a later experiment (experiment 3) showing continuation of the irrelevant speech effect under suppression. Both Macken & Jones (Macken & Jones, 2003) and Neath (2000) have suggested that the latter result may have derived from additional perceptual masking of the auditory stimuli by irrelevant speech, due to the use of synchronous dichotic presentation of the irrelevant and memorial streams. Jones, Macken, & Nichols (2002) found that with a procedure avoiding such acoustic masking the effect of irrelevant speech was completely abolished by articulatory suppression, even for auditory items. However, Hanley & Bakapoulou (2003) have most recently replicated the survival of the irrelevant speech effect under suppression in a study with auditory presentation, wherein the irrelevant speech was limited to only a post-presentation delay period (thus avoiding a masking confound).

To summarize, despite a now vast literature on the effects of articulatory suppression, irrelevant speech, and irrelevant nonspeech, no theoretical account has proven capable of explaining the data in its entirety. A part of the problem, it would appear, is that the experiments originate from labs coming from different conceptual approaches and using different methods. As a consequence, for each type of irrelevant information, “although the main effect is well-established, there exists much uncertainty about the reliability, replicability, and interpretation of the secondary effects and interactions” (Neath et al., 2003, p. 1269). Given difficulties in evaluating competing theories on the basis of these “secondary effects and interactions,” the present study sought to apply a different type of data, based on the neuroanatomical and temporal patterns associated with each irrelevant information effect, to assess alternative accounts.

Neuroimaging and the Functional Anatomy of Working Memory

The case is made above that constraints on cognitive theory provided by behavioral findings do not strongly endorse one model of working memory in favor of another. Recently, advancements in neuroimaging methods (e.g., fMRI, PET) have established these techniques as an important new source of evidence that can be employed to triangulate on a specific cognitive theory.

The “Working Memory Network”

An impressive number of neuroimaging studies have sought to explore the neural basis of working memory. There are now over a hundred such studies investigating working memory for verbal stimuli (e.g., letters, words, digits), and nearly as many for nonverbal stimuli (e.g., spatial locations, abstract objects, faces). What is readily apparent from these myriad studies is the consistent network of neuroanatomical regions implicated in working memory function (D'Esposito et al., 1998; Fiez et al., 1996; Owen, 1997). The major constituents of the verbal

working memory network, in which irrelevant information effects are likely to take place, are shown in Figure 2a. Within the lateral prefrontal cortex at least three distinct sites are implicated, one in a dorsolateral region encompassing Brodmann's areas (BA) 9 and 46 of the middle frontal gyrus (often bilateral), one located more ventrally in the inferior frontal gyrus (BA 44/45/13; Broca's area and the adjacent anterior insular cortex), and one in the premotor cortex (BA 6, bilateral). Activation of the pre-supplementary motor area (pre-SMA, BA 6), located in the medial frontal cortex is also consistent, and this activation often encompasses a portion of the anterior cingulate cortex (ACC) found immediately below pre-SMA. In the parietal cortex, activation of the dorsal aspect of the supramarginal gyrus (BA 40, bilateral) of the inferior parietal lobule is most reliable. Finally, the lateral hemispheres of the cerebellum are also implicated in numerous studies of verbal working memory. The consistency of this network in verbal working memory studies has been recently confirmed via a quantitative meta-analytic approach (Chein, Fissell, Jacobs, & Fiez, 2002).

A Neuroanatomical Map of Working Memory Processes – The Prevailing View

Almost without exception, Baddeley's multiple-component framework has been used to motivate and interpret prior neuroimaging studies. Tested aspects of the framework include the distinction between verbal and visuospatial maintenance subsystems (e.g., Smith, Jonides, & Koeppe, 1996), the dissociability of storage and rehearsal in verbal maintenance (Awh et al., 1996; Paulesu, Frith, & Frackowiak, 1993), and the assumption of a central executive processor that mediates the behavior of the subsidiary maintenance subsystems (e.g., Collette et al., 1999; D'Esposito et al., 1995; Petrides, Alivisatos, Meyer, & Evans, 1993; Postle, Berger, & D'Esposito, 1999). It is generally agreed that each of these aspects is corroborated by the neuroimaging findings (Hartley & Speer, 2000; Henson, 2001; Smith & Jonides, 1999; Smith,

Jonides, Marshuetz, & Koeppel, 1998). Moreover, a specific mapping between components of the model and particular regions of the brain has been forwarded (e.g., Henson, 2001; Smith & Jonides, 1999; Smith et al., 1998). As shown in Figure 2b, this mapping places the phonological storage component of the verbal maintenance subsystem into the left inferior parietal cortex, the speech-based rehearsal process into Broca's area (with possible additional contributions from the premotor, pre-SMA, and cerebellar areas), and the executive control system into the dorsolateral prefrontal cortex (BA 9/46).

Can Neuroimaging Evidence Adjudicate Between Theories

On the surface, investigations in the domain of verbal working memory reflect a rare success in establishing close links between neuroimaging results and cognitive theory. However, the focus on a single theory of working memory has led researchers to overlook alternative theoretical accounts that may actually prove more accommodating of the data. In a recent review on neuroimaging studies of verbal working memory, my colleagues and I (Chein, Ravizza, & Fiez, 2003) considered whether the same data generally taken as support for the Phonological Loop model could be interpreted meaningfully in the context of an alternative theory (the Embedded-Processes model). On the basis of the sum evidence, we suggested that the data could indeed be fit into (and even seemed to favor) Cowan's attentional account. Thus, despite their adherence to clearly different positions on some major theoretical issues, two alternative theories proved amenable to the same evidence. An important realization of the review, however, was that no attempt has been made to directly test the conflicting predictions of alternative models with neuroimaging techniques. This realization motivated the first experiment of this paper.

II.

EXPERIMENT 1

The goal of the present experiment was to pit the alternative predictions derived from competing theories of working memory against one another using fMRI. Importantly, since each model puts forward a different pattern of predictions regarding the effects of irrelevant information, a within-subjects manipulation of interference from concurrent articulatory suppression, irrelevant speech, and irrelevant nonspeech could plausibly corroborate the predictions of one model, while disconfirming those of the alternative models. Let us review the contrasting positions afforded by the four alternative theoretical frameworks (Figure 1a). The Phonological Loop hypothesis maintains that articulatory suppression, irrelevant speech, and irrelevant nonspeech effects each arise from a separate source (Baddeley, 1986, 2000). In comparison, the O-OER model holds that each effect has the same origin (Macken & Jones, 1995). The Feature model, meanwhile, treats the effects of articulatory suppression and irrelevant speech as common, while irrelevant nonspeech effects are presumed to have a separate cause (Neath, 2000; Neath & Surprenant, 2001). Finally, the Embedded-Processes model assumes that articulatory suppression effects have a unique origin, while irrelevant speech and irrelevant nonspeech effects arise from a common source (Cowan, 1995, 2001). These patterns of similarity and difference form the basis for disparate neuroanatomical predictions that can be tested through neuroimaging techniques, and as argued below, trial-based fMRI is particularly well suited for the undertaking (despite some practical limitations).

While the three irrelevant information effects have not been previously tested in a single neuroimaging study, a pair of fMRI studies conducted by Gruber and von Cramon (Gruber,

2001; Gruber & von Cramon, 2003; related data is also discussed in Gruber & von Cramon, 2001) have explored the neural basis of articulatory suppression effects, and an investigation of irrelevant speech effects using PET methodology has been very recently reported by Gisselgard and colleagues (2003). To explore the effects of articulatory suppression on working memory, Gruber and von Cramon had subjects perform a delayed item-recognition task (Sternberg, 1967) under control (no concurrent processing) and articulatory suppression conditions. Since overt movements distort fMRI signal, a silent suppression task that obviated articulatory movements was employed (behavioral confirmation that significant articulatory suppression effects subsist even in the absence of overt articulatory gestures was also reported). Results obtained across their studies suggest that articulatory suppression has at least two reliable consequences for neural processing. First, it seems to enhance activation in part of the “classic” working memory network, including regions in the bilateral ventral operculum/insula and the left inferior frontal sulcus. Second, it appears to recruit the additional processing resources provided by a separate fronto-parietal network, comprised of at least bilateral anterior frontal (BA 46/10) and bilateral inferior parietal (BA 40) regions (other prefrontal and medial areas are also implicated in separate studies). A third effect of articulatory suppression was also proposed, wherein articulatory suppression causes components of the working memory network to be abandoned (e.g., the left premotor cortex). However, this interpretation is somewhat misleading in that it derives from a statistical approach (termed the “interaction” method) in which regions engaged by silent articulation in the absence of a mnemonic-demand are subtracted from only the concurrent (suppression) working memory condition, and not from the control working memory condition to which it was compared. This approach controls for non-mnemonic aspects of the task, but as a consequence, causes regions engaged equivalently for both types of working

memory trial (suppression and control), but also engaged by silent articulation alone, to be inaccurately reported as less active in the suppression working memory condition.

Gisselgard and colleagues (2003) employed an immediate serial recall paradigm to test the effects of irrelevant speech on working memory. While Gruber and von Cramon's findings with articulatory suppression were not addressed in this study, the effects of irrelevant speech obtained by Gisselegard et al. appear to be opposite to those of articulatory suppression. That is, rather than enhance regional activity, irrelevant speech was reported to reduce PET signal across the "working memory network". These reductions were significant in left superior temporal and right inferior/middle frontal areas, while nonsignificant decreases were also observed in homologous regions of the contralateral hemisphere, and in the left inferior parietal cortex. No recruitment of additional regions during interference from irrelevant speech was found. Three important qualifications regarding these results deserve attention. First, as was done in the studies conducted by Gruber and von Cramon (Gruber & von Cramon, 2001, 2003), assessment of the irrelevant speech effect was made through an interaction approach, whereby data from the control and irrelevant speech working memory conditions were not contrasted directly, but rather, as relative signal differences following subtraction of "appropriately" matched baseline conditions. Thus, areas engaged significantly only when irrelevant speech is present (under both mnemonic and non-mnemonic demands) would have again been overlooked in the analysis. Second, to avoid confounds due to differences in the accuracy of performance under irrelevant speech and control conditions, Gisselgard and colleagues tested working memory performance at a reduced load (six digits) at which their subjects showed equivalent accuracy in both conditions. Thus, the standard behavioral effect of irrelevant speech was absent in the experiment. Third,

due to poor temporal-resolution available with PET, regional contributions to encoding, maintenance, and retrieval phases of working memory are necessarily conflated.

The results obtained across these studies point toward an intriguing functional distinction between articulatory suppression and irrelevant speech effects, in that one seems to enhance activity and the other to reduce it. However, the absence of a within-subjects comparison, the deployment of different working memory tasks across studies, and concern over methodological issues suggest the need for caution in drawing strong conclusions on the basis of these findings. Furthermore, an assessment of irrelevant nonspeech effects on neural processing has yet to be made. These limitations are addressed in the present trial-based fMRI experiment.

There are considerable advantages of trial-based (or event-related) fMRI over PET and blocked fMRI methods when appropriately employed (see e.g., Chein & Schneider, 2003). One important advantage is that with the temporal-resolution afforded by fMRI, the combination of a trial-based paradigm and temporally extended working memory trials allows for an assessment of the unique regional contributions to encoding, maintenance, and retrieval phases (Chein & Fiez, 2001). In addition, the trial-based methodology allows data from specific trials to be sorted *post-hoc*. Accordingly, potential confounding due to performance differences can be assessed by inspection of only the subset of trials for which performance was accurate (or inaccurate). This ability to sort *post-hoc* thus allows performance to be tested under conditions that normally produce the relevant behavioral effects (c.f. Gisselgard et al., 2003). A third relevant benefit of the trial-based approach used in the present study is that it allows for an assessment of the “baseline” fMRI signal collected in the absence of any explicit cognitive process, thus obviating the need to employ the potentially misleading “interaction” analysis used in previous studies.

The use of fMRI to explore the effects of concurrent irrelevant processing does however have its disadvantages. One such disadvantage is that operation of the scanner produces a substantial amount of ambient acoustic noise. Behavioral pilot studies (APPENDIX A) were thus conducted to establish that irrelevant sound effects subsist even in the context of ambient scanner noise. As a further precaution, an attempt was made to attenuate as much scanner noise as possible during the imaging experiment. As mentioned above, the susceptibility of fMRI signal to movement artifacts is a further issue of relevance, since it requires that silent articulation, as opposed to the more frequently employed overt articulation, be used in articulatory suppression conditions. Accordingly, behavioral pilot testing was again employed to confirm that the effects obtained with silent articulatory suppression resemble those obtained with covert suppression (as independently confirmed by Gruber, 2001).

The potential for movement in the scanner presents yet another practical difficulty in that it limits how one can measure subjects' responses. While my colleagues and I have shown that even spoken recall can be effectively employed in a trial-based fMRI paradigm (see Chein & Fiez, 2001)³, the movement issue is most frequently addressed in fMRI research by having subjects perform a recognition task requiring only a brief button press response. However, such recognition tasks may be devoid of the serial maintenance processes thought to underlie irrelevant information effects (Beaman & Jones, 1997). Consequently, the present study employs a *probed recall* (Waugh & Norman, 1965) task for which serial maintenance is required, but only a single item is recalled. Confirmation that this task uses serial maintenance processes is afforded by evidence of monotonic response latencies dependent on the serial position of the probe (a characteristic of serial rehearsal, Sternberg, 1967). Perhaps even more

³ The use of spoken serial recall in Chein & Fiez (2001) required the inclusion of a particularly extended baseline period, and made response coding somewhat unreliable.

importantly, Jones & Morris (1992) report that standard irrelevant speech and articulatory suppression effects are obtained with a probed recall task analogous to that used in the present experiment.

A simple logic can be employed to form predictions. Effects having a common source should influence fMRI signal during working memory processing in the same way. That is, the pattern of brain activity observed under conventional (quiet) working memory conditions should be modified in the same way by separate irrelevant information effects presumed to derive from the same mechanism. Such modification may materialize as an alteration of the signal magnitude or temporal processing within the “classic” working memory network, or as an actual shift in the neuroanatomical substrates of performance (i.e. a change in the set of regions activated during working memory). By contrast, effects having different sources should accordingly have dissociable consequences for brain activity. Again, these distinct consequences may surface as changes in the engagement of working memory areas, or as more global shifts in the underlying neuroanatomy. Importantly, the predictions formed through this logic are neutral with respect to the type of neural modulation expected for each effect (e.g., a magnitude increase or decrease). Moreover, while interpretation of the results can be informed by proposed mappings of a given model onto the brain (e.g., Chein et al., 2003; Cowan, 1999; Smith & Jonides, 1997)], the logic of the experiment is similarly neutral to specific anatomical localization, and relies only on the assumption that distinct processes are localizable to discrete brain areas.

Participants

Fourteen right-handed, native English speaking, subjects (mean age ~ 22 years, range 19-29, 8 females) selected from the University of Pittsburgh community volunteered to take part in the

fMRI experiment. All subjects were naïve to the specific hypotheses being tested, but had completed a brief prior behavioral session to demonstrate their individual sensitivity to the types of irrelevant information being tested, and to ensure roughly equivalent working memory spans across subjects (80-95% accuracy on quiet trials). Participants gave informed, written consent, and received monetary compensation. All subjects reported normal hearing and normal, or corrected-to-normal, vision.

Design

The experiment included four working memory conditions [quiet (WMQ), concurrent silent articulatory suppression (WMAS), concurrent irrelevant speech (WMIS), concurrent irrelevant nonspeech (WMIN)] and three non-mnemonic conditions [silent articulatory suppression (AS), irrelevant speech (IS), irrelevant nonspeech (IN)]. Subjects completed 13 experimental blocks,⁴ each lasting 6.6 minutes, comprised of 11 task trials (two trials of each working memory condition, and one trial of each non-mnemonic condition). In total, subjects completed 26 trials for each working memory condition, and 13 trials for each non-mnemonic condition. The trials were sampled in a pseudo-random fashion such that no two successive trials were of the same condition. The experimental session lasted for two hours.

Stimuli

A list of seven items was presented for each working memory trial. The lists were constructed by sampling seven items in random order (without replacement) from the consonants B, F, H, K, L, M, Q, R, S, and Z. The letters were displayed sequentially, just above a centrally located fixation cross, in upper-case, 26-point, white, Garamond font on a black background. For non-

⁴ The full experimental session could not be finished for two subjects. Consequently, one subject completed only ten blocks, and the other only seven.

mnemonic trials, each of the to-be-remembered letters was replaced by a pair of hyphens (--) of the same font color and size as the letters.

Irrelevant background sounds were constructed using Goldwave (GoldWave Inc., Newfoundland, CA) sound editing software. Irrelevant background speech sequences consisted of the spoken digits one through four, presented in pseudo-random order (the same digit was never spoken twice in succession). These speech sequences were derived from digital recordings of a male speaker, obtained at 16-bit resolution and a sampling rate of 44 kHz. After recording, each spoken digit was isolated and edited to be 350 ms long. Eight irrelevant speech sequences, lasting 20 s each, were then assembled by sampling one of the four speech tokens (digit) once every 500 ms (i.e. a 150 ms gap separated each speech sound).

Irrelevant nonspeech sequences consisted of changing-state broadband noise bursts, and were closely matched to the changing-state sequences used by Tremblay, Macken, & Jones (2001). White noise (with equal energy over audible frequencies) was generated digitally, and then filtered at each of five center frequencies: 250, 500, 1000, 2000, and 4000 Hz. As in Tremblay et al. (2001), the filter was designed to produce broadband noise with a center frequency-to-bandwidth ratio of 1.66, and to thus yield sounds with a low degree of tonality. Importantly, the resulting sounds would not be mistaken for speech (i.e., the broadband noises are not speech-like). Subjects were also explicitly informed that the noise bursts were computer-generated. As with the speech sequences, sound tokens lasting for 350 ms were created from the five broadband noises associated with each center frequency. These five sound tokens were then assembled in pseudo-random fashion at a rate of one token every 500 ms (with 150 ms gaps) to form irrelevant nonspeech sequences. Eight nonspeech sequences, each lasting 20 s, were constructed.

All irrelevant background sounds (speech and nonspeech) were delivered through MRI compatible headphones (Avotec Inc., Stewart, Florida) at approximately 70dB (A), as measured by a digital sound level meter (Extech Instruments, Waltham, MA). The headphones attenuated approximately 15-20dB of the ambient sounds produced by the MRI scanner during data collection, and additional sound-insulating material was packed around the headphones to further reduce the amount of scanner noise heard by participants. For all participants, an initial sound test was conducted to insure that the irrelevant background sequences were audible well above the operating sounds of the scanner.

Procedure

Cognitive Task Procedure

Subjects were scanned while performing a probed recall task under various irrelevant information conditions. The task required that subjects view a series of items, maintain the series over a delay, and then recall a specific item when given the item that preceded it in the series as a probe. Figure 3 shows a schematic diagram of a task trial. Experimental programming and presentation was implemented with the E-Prime experimental software suite (Psychology Software Tools, Pittsburgh).

Working Memory Trials

Trials associated with the working memory conditions differed only according to the type of irrelevant information present during the trial, as described below. Each working memory trial began with a brief instruction period that indicated the nature of irrelevant information, if any, that would be imposed. The subsequent encoding period consisted of seven to-be-remembered English letters presented sequentially at a rate of one item per second (on for

0.8 s, off for 0.2 s). Following the final list item, a *wait* prompt appeared, and remained visible on the screen for the duration of 10 seconds. Subjects were instructed to covertly maintain the list items throughout this delay period. To avoid strategic confounding of the results, subjects were asked to refrain from employing intentional mnemonic devices (e.g., chunking) that would reduce the working memory load.

At the end of the delay, an item-probe appearing in the middle of the display prompted the subject to begin recall. The probe item was always a to-be-remembered letter from one of the first six serial positions of the effective trial.⁵ Subjects were instructed to respond to the recall probe by writing the successive item from the series (i.e. the letter that followed the probe letter during encoding) onto a notepad. Accordingly, on a given working memory trial, the subject was required to respond with a specific item from one of serial positions two through seven. It should be highlighted that while this working memory task requires that only one item be recalled per trial, subjects had to maintain the entire series to support accurate responding (see also Sternberg, 1967).

The positioning of the subjects in the scanner did not allow them to see the response notepad, which rested against the subjects' legs. Accordingly, to promote the likelihood of obtaining legible responses, a fresh response sheet was provided for each block, and subjects were explicitly instructed on the appropriate placement of each of the 11 responses (one per trial) given in a block. Responding was allowed for 4 seconds, following which time the recall probe was removed from the display.

For the remainder of the trial, subjects passively viewed a centrally located fixation cross. The fixation remained on the display for 12 seconds, allowing the hemodynamic response

evoked by cognitive components of the task to decay back to baseline. Subjects were encouraged to treat this baseline period as an opportunity to relax.

Non-mnemonic Trials

The inclusion of non-mnemonic trial types allowed for the identification of brain regions engaged by the “irrelevant” processes in the absence of a working memory demand. Accordingly, trials associated with the three non-mnemonic conditions were closely matched to the working memory trials with respect to visual input, response, and irrelevant information, but differed from the working memory trials in that they placed no demands on the memory system. To-be-remembered letters were not shown in non-mnemonic trials, and instead, subjects saw a pair of hyphens flash seven times at the same presentation rate (0.8s on, 0.2s off). Without items to retain in memory, subjects were instructed to simply rest during the ensuing delay period (except when required to engage in articulatory suppression, see below). The recall probe for non-mnemonic trials was again a pair of hyphens, to which subjects responded by writing a pair of hyphens on the notepad.

Irrelevant Information Type

Irrelevant information type was manipulated from trial to trial, with four possible conditions: quiet (i.e., no irrelevant information), irrelevant speech, irrelevant nonspeech, and articulatory suppression. The irrelevant information was identical for working memory and non-mnemonic trials, but only the working memory trials were performed under quiet conditions.

⁵ Interference effects are largest in the latter part of the serial position curve. To optimize the likelihood of obtaining significant effects, selection of the probe item was accordingly biased with serial positions 1 and 2 each used as the probe on 10% of trials, and serial positions 3 through 6 each used as the probe on 20% of trials.

The type of irrelevant information associated with a given trial was indicated by a colored frame first appearing around the stimulus display during the trial instruction period. The frame was color-coded allowing subjects to determine which type of irrelevant information was being tested. The colored frame remained visible on the display throughout the encoding and delay periods (20 seconds), and was removed as the recall probe appeared. On quiet trials, subjects were told to simply ignore the frame and to continue performance of the basic probed recall task. On irrelevant speech and nonspeech trials, one of the eight prearranged sound sequences (selected at random) was initiated and terminated concurrent with the appearance and disappearance, respectively, of the colored frame. Accordingly, the background sounds were presented during the encoding and delay stages of the trial for a total duration of 20 seconds. Subjects were instructed to ignore the background sounds, and to focus on the working memory task. On articulatory suppression trials, subjects were required to initiate covert repetition of the word “*the*” at an approximate rate of two repetitions per second and as soon as the appropriately colored frame appeared on the display. Silent articulatory suppression continued at this rate until the frame disappeared from the screen, again for a total duration of 20 seconds. To avoid movement artifact in the imaging data, subjects were instructed to refrain from any overt movements of the articulatory musculature during silent articulation.

FMRI data acquisition

Scanning was conducted on a 3-Tesla head-only Siemens Allegra magnet equipped with a standard transmit/receive head coil. Subjects lay supine, and stimuli were projected onto a visual display positioned inside the magnet’s bore (viewed through a mirror placed above the subjects’ eyes). Synchronization of the experimental stimuli with scanner activity was handled by the IFIS software system (Psychology Software Tools, Pittsburgh).

Prior to functional scanning, a 34 slice oblique-axial structural series was collected parallel to the AC-PC plane with a T1-weighted inversion recovery pulse sequence (TE = 14 ms, TR = 1570 ms, FOV = 200 mm, slice thickness = 2.7 skip 0.3, flip angle = 180, inversion time = 800 ms). This slice prescription provided coverage from the top of the brain through the upper third of the cerebellum in all subjects. The structural series served as an “in-plane” anatomical reference for all functional series, which were acquired in the same slices using a T2*-weighted echo-planar imaging (EPI) sequence (TE=30, TR=2000, FOV=200 mm, slice-thickness=3.0 skip 0 mm, flip angle=70, in-plane resolution = 3.125 mm). Functional data were collected in thirteen separate runs, each associated with one block of the cognitive paradigm. Each run lasted for 6 minutes 42 seconds, and included 201 image acquisitions, the first three of which were discarded. To support more precise anatomical localization, a separate high-resolution 3D structural volume (Siemens MPRAGE) was also collected for each subject.

FMRI data analysis

Data analysis was conducted off-line using select utilities from a range of neuroimaging software packages (Brain Voyager, AIR, NIS, FSL, AFNI), with format conversion and integration provided by Fiswidgets (Fissell et al., 2003). A series of preprocessing steps were employed to correct for artifacts and individual subject differences. To compensate for variation in acquisition timing, a slice-time correction using sinc interpolation was first applied. Images were then adjusted for subject motion through a six-parameter rigid-body automated registration algorithm (Woods, Cherry, & Mazziotta, 1993). Finally, data from each functional run was further corrected to adjust for non-specific linear trends.

In order to obtain group composite results, structural images from each subject were transformed into a common reference space using first a linear (12-parameters), and then a non-

linear (60-parameters), alignment step (Woods, Grafton, Watson, Sicotte, & Mazziotta, 1998). The same transformation matrix was then applied to the functional data. Global mean scaling (to account for differences in subject means) and 3D isotropic Gaussian smoothing (8mm FWHM) were also applied to adjust for between-subjects differences. For final reporting and anatomical localization, the reference anatomy and statistical maps were warped into standard stereotaxic space (Talairach & Tournoux, 1988).

Statistical analysis of the functional data employed least-squares estimation based on the general linear model (GLM) approach, allowing fMRI BOLD signal changes occurring during particular temporal stages of the task trial to be assessed (see Zarahn, Aguirre, & D'Esposito, 1999). The full model included four temporally shifted covariates (shown in Figure 3) for each task condition. The four covariates were formed by convolution of a canonical model of the hemodynamic response⁶ (Boynton, Engel, Glover, & Heeger, 1996) with a square-wave function that was time-locked to one of four specific sub-stages of the trial: encoding (e), early delay (d1), late delay (d2) or recall (r). While the two middle covariates (d1 & d2) are of greatest relevance in assessing working memory function, the inclusion of the surrounding covariates allowed encoding and retrieval components of the task to be assessed, and caused variance explained by the d1 and d2 covariates to be specific to delay-period activity (Zarahn et al., 1999).

As detailed in the results section, several statistical contrasts based on this full model were conducted. To form group-composite statistical maps, voxel-wise parameter estimates (coefficients) provided by the GLM were first obtained for each subject independently (using the spatially normalized data). A t-test of the significance of the subjects' coefficients at each voxel

⁶ The use of a canonical hemodynamic model may be problematic in that different subject, and even different regions within a subject may produce a differential hemodynamic response. Accordingly, statistical contrasts were repeated using a more flexible inferential approach similar to that employed by Chein & Fiez, 2001. Highly consistent results were obtained, and only the GLM findings are reported.

(relative to zero) was then conducted, thus constituting a random-effects analysis. All statistical maps were thresholded using a false discovery rate (FDR) algorithm (Genovese, Lazar, & Nichols, 2002), with the probability of a false detection set at $q = 0.01$.⁷

Results

Behavioral Results

Probed recall task performance was analyzed to identify the behavioral effects of silent articulatory suppression, irrelevant speech, and irrelevant nonspeech on working memory. Subject accuracy in each working memory condition was calculated by determining the proportion of trials on which subjects correctly recalled the item that succeeded the probe. The mean accuracy of performance in each condition is shown in Figure 4. The overall disruptive effects of irrelevant information were first assessed in a one-way repeated measures ANOVA with irrelevant information type (WMQ, WMAS, WMIS, WMIN) as a within-subjects factor, which produced a significant result [$F(3,13)=12.61$, $p < 0.001$]. Planned comparisons were used to contrast performance under each of the concurrent processing conditions to that in the quiet condition (WMAS vs. WMQ, WMIS vs. WMQ, WMIN vs. WMQ). Each type of irrelevant information produced a performance decrement, with the proportion of accurate trials under articulatory suppression [mean = 0.49, SD = 0.19, $T(13) = 6.12$, $p < 0.001$, one-tailed], irrelevant speech [mean = 0.58, SD = 0.17, $T(13) = 4.56$, $p < 0.01$, one-tailed], and irrelevant nonspeech [mean = 0.68, SD = 0.15, $T(13) = 2.39$, $p < 0.05$, one-tailed] all significantly reduced relative to quiet (mean = 0.77, SD = 0.10). These behavioral effects were also very reliable within subjects (all subjects showed a performance decrement with suppression, 13 of 14 with

⁷ The FDR approach applies a correction for multiple tests that is less conservative than probability adjustments based on the Bonferroni method.

irrelevant speech, and 11 of 14 with irrelevant nonspeech). Additional *post-hoc* contrasts (Newman-Keuls) yielded further significant differences between the articulatory suppression and both irrelevant sound conditions ($p < 0.01$), but a nonsignificant difference between irrelevant speech and irrelevant nonspeech ($p = 0.07$).

Imaging Results

Working Memory Effects

The first goal of analysis was to localize the network of regions supporting short-term maintenance during probed recall task performance. To identify these regions, the four covariates associated with quiet working memory trials (WMQ) were tested for significant contributions to the overall variance in each voxel's time-series. This analysis revealed regions contributing to the encoding, maintenance, and/or retrieval of information in working memory in the absence of irrelevant information. Results from this analysis are summarized in Table 1.

Since the essential function of working memory is to maintain information in the absence of external stimulation (i.e. over a delay), analysis of the two delay-period covariates (d1 & d2) could be regarded as the purest measure of a region's involvement in working memory. Thus, voxels exhibiting significant loading on these two delay covariates were of greatest interest. Areas exhibiting significant delay-based activation are shown in Figure 5. Several frontal lobe regions were significant for both the early (WMQ_{d1}) and late (WMQ_{d2}) delay period covariates. These included medial frontal sites in the pre-SMA (BA 6/32) and anterior cingulate cortex (BA 24/32), a left premotor region (precentral gyrus, BA 6), a ventral left inferior frontal area spanning the opercular and triangular parts (BA 44/45), and bilateral sites at the confluence of the insular and inferior frontal cortices (BA 45/13, hereafter referred to as anterior insula). Additional regions significantly engaged for only the early delay period (WMQ_{d1}) included the

right premotor area (BA 6), the dorsal part of the left inferior frontal gyrus (BA 44/9), the bilateral basal ganglia (putamen), and bilateral cerebellar sites. Although portions of the dorsolateral prefrontal cortex were significant in the early delay, additional middle frontal activations (left middle frontal gyrus, BA46; left precentral and middle frontal gyri, BA 6/9) also appeared in the later half of the delay period (WMQ_{d2}), as did a left middle temporal (BA 21) area.

Foci of activation associated with the encoding and retrieval stages of task performance were similarly assessed by identifying regions with significant contributions from the encoding (WMQ_e) and recall (WMQ_r) covariates in quiet working memory trials. Several encoding and retrieval related activations were found in regions overlapping those implicated in delay-based processing (see Table 1). In addition, bilateral parietal regions (BA 7/40 and BA 40/39) and a left fusiform (BA 37) area that did not show up during analysis of the delay covariates were found to exhibit significant involvement in both encoding and recall. In encoding only, a homologous right lateralized fusiform activation, and bilateral extrastriate (BA 18) regions were also detected. Additional recall-related activity was observed bilaterally in the primary sensorimotor cortices (BA 4/3/2), thalamic nuclei, and anterior middle frontal gyri (BA 10), as well as in the medial cerebellum.

Irrelevant information Effects

The primary objective of the experiment was to characterize the neural correlates of articulatory suppression, irrelevant speech, and irrelevant nonspeech effects in working memory. To examine the neuroanatomical sources of these effects, regions exhibiting significant delay-related activity in the working memory analysis (i.e. those showing activation associated with

covariates WMQ_{d1} and/or WMQ_{d2}) were treated as regions-of-interest (ROI's), and were further probed for effects of irrelevant information. To identify ROI's exhibiting significant irrelevant information effects, the time series from each region was submitted to a set of general linear tests based on the covariates for each trial sub-stage (see Figure 3). Specifically, the four trial covariates from each condition were used to construct twelve linear contrasts, each comparing signal from an irrelevant information condition to that in the quiet condition for a particular sub-stage, as follows: articulatory suppression contrasts - WMAS_e vs. WMQ_e, WMAS_{d1} vs. WMQ_{d1}, WMAS_{d2} vs. WMQ_{d2}, and WMAS_r vs. WMQ_r; irrelevant speech contrasts - WMIS_e vs. WMQ_e, WMIS_{d1} vs. WMQ_{d1}, WMIS_{d2} vs. WMQ_{d2}, and WMIS_r vs. WMQ_r; irrelevant nonspeech contrasts - WMIN_e vs. WMQ_e, WMIN_{d1} vs. WMQ_{d1}, WMIN_{d2} vs. WMQ_{d2}, and WMIN_r vs. WMQ_r. Regions showing significant differences in these contrasts are detailed in Table 2.

Articulatory Suppression Effects. In general, articulatory suppression was found to increase activity in working memory regions. Significant activity enhancements were found in five of the sixteen working memory (e.g., delay-related) ROI's. These included the pre-SMA (BA 6/32), premotor cortex (lateral BA 6), left dorsal and ventral inferior frontal gyrus (BA 44/9 and BA 45/44, respectively), and the left anterior insula (BA 45/13). In all of these regions, the increase in activity was significant in a contrast of the encoding covariate for articulatory suppression trials to the encoding covariate for quiet trials (WMAS_e vs. WMQ_e). In the pre-SMA, ventral inferior frontal, and anterior insular areas, the increase with suppression was shown to persist into the delay via a linear contrast of the early delay covariates for each condition (WMAS_{d1} vs. WMQ_{d1}). Similar patterns of increase that failed to reach statistical significance were also present in the anterior cingulate cortex (BA 24/32), bilateral cerebellum, and right lateralized homologues of the premotor and anterior insular regions. The only

additional significant difference between suppression and quiet trials was a relative decrease of activity under suppression in the left basal ganglia (putamen), identified by a contrast of the late delay covariates (WMAS_{d2} vs. WMQ_{d2}). No differences were present in the recall period (WMAS_r vs. WMQ_r), by which time subjects had terminated articulatory suppression.

Irrelevant Speech Effects. In contrast to the effects obtained under articulatory suppression, irrelevant speech tended to reduce activity in working memory areas. Interestingly, this reduction emerged later in the trial than did the increases observed with concurrent articulatory suppression. Specifically, a contrast of the encoding period covariate for irrelevant speech and quiet trials (WMIS_e vs. WMQ_e) produced no significant results. However, significant decreases in the magnitude of regional activity were found within the anterior cingulate, left dorsal and ventral inferior frontal, bilateral anterior insula, and left basal ganglia ROI's in a contrast based on the early delay covariates (WMIS_{d1} vs. WMQ_{d1}). These decreases remained significant into the late delay period (WMIS_{d2} vs. WMQ_{d2}) in the left ventral inferior frontal, left anterior insula, and left basal ganglia regions.

Concurrent irrelevant speech also produced a significant *increase* in activation in the left middle temporal (BA 21) ROI that had been identified as active during only the latter part of the delay period for WMQ trials. This significant increase reflected an engagement of the middle temporal cortex earlier in the delay period (WMIS_{d1} vs. WMQ_{d1}) only when concurrent irrelevant speech was present. Once again, no differences were found during the recall period (WMIS_r vs. WMQ_r).

Irrelevant Nonspeech Effects. The results obtained from comparison of concurrent irrelevant nonspeech to quiet working memory trials were highly consistent with those obtained for the concurrent irrelevant speech contrasts. Significant irrelevant nonspeech effects were

found in the anterior cingulate, the left dorsal and ventral inferior frontal gyrus, the left anterior insula, and the left basal ganglia. A nonsignificant, but similarly patterned difference was also present in the right anterior insula. As with irrelevant speech, these irrelevant nonspeech effects could be characterized as reductions in the magnitude of working memory activity occurring specifically during the delay portion of the trial. A contrast for the encoding period ($WMIN_e$ vs. WMQ_e) again produced no significant differences. Meanwhile, activity reductions from irrelevant nonspeech were significant in all listed regions during the early delay period ($WMIN_{d1}$ vs. WMQ_{d1}), and for the left ventral inferior frontal and left anterior insula in the late delay period ($WMIN_{d2}$ vs. WMQ_{d2}). No differences were obtained in the recall period, nor did any region exhibit an increase in activity with concurrent irrelevant nonspeech.

Irrelevant information effects in correct-only trials. A concern often raised in the imaging literature is that apparent functional neuroanatomical differences may derive solely from differences in the accuracy of performance, rather than from actual processing differences induced by the intended experimental manipulation (e.g., Barch et al., 1997). It seems unlikely that such an explanation could account for the present results, in that distinct conditions having similar effects on performance were found to have opposite effects on neural activity (increases with WMAS, decreases with WMIS and WMIN). However, it could be argued that the additional performance decrements in the WMAS condition were responsible for some of the observed differences. To address this potential confound, the data were sorted *post-hoc* to allow examination of the subset of trials for which subjects produced an accurate response. Analysis of correct-only trials produced a pattern of irrelevant information effects qualitatively consistent with those observed in the full dataset (though sub-sampling of correct-only trials limits the

statistical power of these tests). In some regions (e.g., left anterior insula) the size of the irrelevant information effects even appeared to be enhanced for correct-only trials.

Competition for Cognitive Resources

A common assumption among the considered models of working memory is that irrelevant information effects derive from competition between the primary working memory task and the secondary interference conditions (in some models the competition is for processing resources, and in others it is for representational resources). In neuroanatomical terms, one might expect that the locus of competition could be revealed as shared territory (overlap) between the working memory network and the set of areas engaged when interfering conditions are present in the absence of a working memory demand. To identify the possible anatomical loci of such resource competition, a set of activation maps was generated from the delay covariates associated with each of the non-mnemonic trial types (AS, IS, IN), and these maps were inspected for anatomical overlap with the ROI's identified in the working memory effects analysis. It should be noted, however, that the limited number of non-mnemonic trials obtained from each subject (thirteen) is below the minimum number of trials normally suggested to achieve statistical reliability in a trial-based design (Chein & Schneider, 2003).

For non-mnemonic articulatory suppression trials (AS), only the left precentral gyrus was found to overlap with the identified set of working memory regions, though activation in this condition was notably weaker than in the memory conditions. For non-mnemonic irrelevant speech trials, an overlapping activation was also found in the left middle temporal gyrus. No other delay-based activity from non-mnemonic trials occurred within the working memory ROI's. That is, no other regions showed significant activity during the delay portion of non-mnemonic trials.

Given the limited degree of overlap between delay-based activity in the mnemonic and non-mnemonic conditions, exploration of non-mnemonic trials was extended in two ways. First, non-mnemonic activations significant during encoding or retrieval stages in the defined ROI's were assessed. This post-hoc analysis revealed an additional activation for articulatory suppression trials during only the encoding period in the right cerebellar ROI.

To further extend the search for non-mnemonic activations, a brain-wide test of the delay covariates in non-mnemonic trials was conducted as a second *post hoc* analysis. For non-mnemonic silent articulation trials, this analysis revealed delay-based activation in a supplementary motor region that was posterior to, and non-overlapping with, the pre-SMA site implicated in quiet delay-based processing. Non-mnemonic irrelevant speech and irrelevant nonspeech produced very strong activation of the primary auditory (and surrounding) cortices for encoding (e) and delay (d1 and d2) covariates. No other regions were significantly activated in the non-mnemonic irrelevant information conditions.

Recruitment of Compensatory Resources under Interference from Irrelevant Information

The work of Gruber and von Cramon (Gruber & von Cramon, 2001, 2003) suggests that partially distinct cortical networks may be used to support working memory performance when it occurs with and without concurrent interference. That is, working memory performance under interfering conditions may be supported by an additional set of cognitive processes, and thus, by distinct brain regions from those engaged during quiet working memory. A similar argument is found in the cognitive theoretical literature, where it has been suggested that irrelevant information can lead to the abandonment of processes normally used to support working memory (e.g., phonological storage and rehearsal), and to the recruitment of compensatory processes (e.g., Larsen & Baddeley, 2003). Thus, a potential limitation of the ROI-based approach

employed above, which considered the data from only quiet working memory (WMQ) trials to identify the ROI's, is that it may have excluded regions engaged to support working memory only under interfering conditions. To detect any such regions, the data from each type of working memory irrelevant information trial (WMAS, WMIS, WMIN) was analyzed separately by an analogous approach to that used to identify maintenance regions for quiet working memory trials (i.e., by identifying voxels in which the delay covariates, d1 and d2, from a given irrelevant information trial type explained a significant portion of the variance).

All three working memory irrelevant information conditions engaged the same broad network of regions as was identified in the quiet working memory trial analysis. For concurrent articulatory suppression trials, the regions engaged in delay-based processing almost completely subsumed the set of voxels comprising the quiet working memory network. Interestingly, despite reduction of the signal with irrelevant speech (WMIS) and nonspeech (WMIN) conditions, activity associated with these conditions also remained above the statistical criteria in all working memory ROI's (though select voxels in certain ROI's did fall below the statistical threshold).

Beyond those areas implicated in the working memory network for quiet trials, concurrent articulatory suppression trials (WMAS) also produced significant delay-period activity in bilateral anterior middle frontal gyri (BA 46/10), bilateral inferior parietal lobes (BA 40/39, immediately anterior to the parietal activations observed for quiet encoding), and a right cerebellar area (lateral to that found for the quiet encoding and early delay periods). Figure 6 specifies the stereotaxic localization and temporal patterns associated with these areas. While activation did not reach statistical significance for any of the other working memory trial types,

inspection of the time-series in these regions indicated that similar, sub-threshold, temporal patterns were present for quiet and concurrent irrelevant sound trials.

As expected given the additional auditory input associated with concurrent irrelevant speech and nonspeech trials, these irrelevant sound conditions also produced large activations in the primary auditory and adjacent cortices. However, no additional areas were recruited to support performance in the presence of irrelevant sounds of either type.

Discussion

This trial-based fMRI experiment represents the first within-subjects test of irrelevant information effects (articulatory suppression irrelevant speech, and irrelevant nonspeech) in neuroimaging, and is the first fMRI study of verbal working memory to employ a delayed, probed-recall task. With respect to the primary goal of the experiment, the main finding was that the articulatory suppression effect was dissociated from the effects of irrelevant speech and nonspeech in the directional valence and timing of the influence it exerts on cortical function. Specifically, articulatory suppression caused a generalized *increase* in the BOLD fMRI response relative to control working memory conditions, and this increase tended to materialize *early* during task trials in the affected subset of working memory regions. In contrast, both irrelevant speech and irrelevant nonspeech caused a distributed *decrease* in the signal, which was found to emerge slightly *later* in the trial (especially in inferior frontal and anterior insular regions). A partial dissociation of the effects is also apparent through examination of their anatomical loci, in that only suppression altered activity in pre-SMA and premotor regions.

Several consistencies with previously published work point to the reliability of the results afforded by the present experiment. Although the use of probed recall is novel to fMRI, the obtained pattern of working memory activity closely parallels that observed in an earlier trial-

based fMRI study of verbal working memory using serial, rather than probed, recall (Chein & Fiez, 2001). In both studies, delay-based processing was found to be supported by a principally frontal network including pre-SMA, premotor, middle and inferior frontal, anterior insular, and basal ganglia regions (though the localization of basal ganglia activations appears to differ slightly across studies). Engagement of these regions in verbal working memory is also highly consistent with the broader literature (Cabeza & Nyberg, 2000; Smith & Jonides, 1999; Fiez, 1996; Chein et al., 2002). Among other similarities between Chein & Fiez (2001) and the present study, both also found temporally transient delay-period responses in left dorsal inferior frontal and cerebellar regions, and weak (nonsignificant) delay-based inferior parietal activation. In that these latter findings (particularly the weak inferior parietal activation) are somewhat less compatible with results obtained in past studies using recognition procedures (e.g., N-back, delayed-item-recognition) or methods with poorer temporal resolution (i.e. PET and blocked-fMRI), the present study provides an important replication of our earlier results and demonstrates their generalizability to another recall-based paradigm (i.e., probed recall).

The present findings also generally converge with previous neuroimaging studies with regard to the consequences of irrelevant information in working memory. As in the prior work of Gruber and von Cramon, the behavioral effect of articulatory suppression is shown to correspond with relative increases in the activation of at least the left inferior prefrontal and bilateral anterior insular regions. The present observation of similar increases in the pre-SMA and left precentral regions also appears to be consistent, though this is somewhat difficult to assess due to the “interaction” method used in the prior studies. Specifically, Gruber & von Cramon (2003) reported significant activation of analogous pre-SMA and left precentral regions during silent articulation performed in the absence of a mnemonic demand (see Gruber & von

Cramon, 2003, Table 2), but subtracted out these activations in the process of comparing the articulatory suppression to control working memory conditions. While non-mnemonic articulatory engagement of the left premotor cortex was also found in the present study, the statistical approach ensured that data from this condition did not influence the detection of irrelevant information effects present during working memory trials. Importantly, this difference in statistical approach explains a further apparent disparity between the present findings and those of Gruber and von Cramon (2003) in that the present study produced no evidence that verbal working memory regions are abandoned during articulatory suppression.

Gruber (2001) and Gruber & von Cramon (2003) assert that the demands of articulatory suppression cause subjects to recruit additional maintenance resources, as evidenced by their observation of an additional “bilateral prefrontal-parietal network” specifically during concurrent articulatory suppression trials. Interestingly, they note that this recruited network is unlikely to reflect domain-general (e.g., central executive) contributions, since the same regions are not engaged to support visuospatial working memory under correspondingly damaging interference. The results of the present study replicate the emergence of these additional regions under articulatory suppression, but shed further light on interpretation by providing a characterization of their temporal profile in all task conditions (Figure 6). From these profiles, it is clear that while articulatory suppression drives activation above the statistical threshold, the same regions are similarly engaged at sub-threshold levels in each of the other working memory conditions. The data thus suggest that rather than being recruited only when articulatory mechanisms are burdened, the processes supported by these regions are just more heavily emphasized under articulatory suppression. It should be noted, however, that the parietal activations obtained in the present study (under concurrent suppression) are spatially consistent with activations commonly

observed in quiet verbal working memory, while Gruber and von Cramon report a somewhat more lateral (and atypical) site.

The results from the present experiment are also broadly consistent with the irrelevant speech effects reported by Gisselgard et al., (2003). In both, the behavioral disruption produced by irrelevant speech is shown to be reflected as a distributed reduction of activity in the working memory network. Gisselgard et al., however, obtained significant reductions in only the left superior temporal gyrus, with a nearly significant reduction in the right prefrontal cortex, neither of which is generally treated as a constituent of the “classic” working memory network (as revealed in prior neuroimaging studies). The authors suggest that left superior temporal activation has been found in some previous working memory studies (Paulesu et al., 1993), and likely reflects early phonological processes necessary for instantiating working memory representations (Hickok & Poeppel, 2001). Nonsignificant trends were also apparent in more typical left prefrontal and left parietal components of verbal maintenance. In the present study, significant irrelevant speech effects were found to be somewhat more widespread, and occurred within regions more commonly implicated in verbal working memory processing (anterior cingulate, left dorsal and ventral inferior frontal, and bilateral anterior insular sites). This difference in the sensitivity of the present experiment to irrelevant speech effects likely derives from an advantage of trial-based fMRI. Namely, the PET methodology employed by Gisselgard and colleagues demanded that the statistical contrasts used to detect effects be based on data from the whole working memory trial. Given that irrelevant speech effects were found in the present study to occur only during the delay interval, such course analysis of the trials could have precluded detection of these relatively subtle effects.

By demonstrating the dissociability of articulatory suppression from irrelevant speech in a within-subjects experimental design, the present study corroborates the apparent differences suggested by prior neuroimaging studies. In addition, the current findings extend these earlier results in a number of important ways. Perhaps most relevant to the theoretical debate that motivated the experiment, the neural effects of irrelevant nonspeech are shown to be nearly identical to those of irrelevant speech. In particular, irrelevant nonspeech produced a reduction in the magnitude of activity in the same working memory regions as did speech, and at the same time during the working memory trial. Aside from minor differences due to statistical thresholding effects (e.g., right anterior insula), the only differentiation of irrelevant speech from irrelevant nonspeech was present in the pattern of left middle temporal activity. This region was found to be active in the early delay-period for only irrelevant speech trials (both mnemonic and non-mnemonic), and not so for any other condition. However, the fact that this area is almost never implicated in prior neuroimaging studies of working memory, and that it just attained significance in the present study, suggests that results from this region should be treated with caution.

By providing a window into the timing of cortical function, the present study further reveals that irrelevant information effects transpire as somewhat transient, yet differentially timed, modulations of regional activity. As discussed above, this finding has practical importance in suggesting that experimental designs for which sub-stages of a trial can be isolated will have greater sensitivity to the effects. Moreover, the distinct timing of articulatory suppression effects from those of irrelevant speech and nonspeech presents another example of their functional neuroanatomical separability (and suggests a novel behavioral approach to obtaining dissociations, as implemented in Experiment 2 of this paper). The present findings

also demonstrate that conditions producing similar decrements in working memory performance can induce opposite directional changes in the magnitude of regional activity, depending on the nature of the disrupting information. Perhaps more importantly, the data show that the effects of irrelevant information persist both in the presence and absence of behavioral differences, as confirmed by examination correct-only trials.

The four theories reviewed in the introduction to this paper, the Phonological Loop model, the O-OER model, the Feature model, and the Embedded-Processes model, each afforded a different prediction for the imaging study. The phonological loop predicted that all three manipulations of irrelevant information would have dissociable effects. Although the results indicate that articulatory suppression can be distinguished from irrelevant sound effects, they fail to corroborate the position that irrelevant speech and irrelevant nonspeech effects have unique origins. The O-OER model predicted that all three manipulations would have similar effects. While this view nicely addresses the similarities between irrelevant speech and nonspeech, it struggles to explain the clear dissociation of articulatory suppression from these irrelevant sound conditions. The same challenge is presented for the Feature model, from which it was predicted that irrelevant speech and articulatory suppression would have comparable influences on neural processing. However, the remaining alternative forwarded by the Embedded-Processes model accurately predicted the outcome of the study, wherein articulatory suppression was shown to be distinct from the irrelevant sound effects, but no further distinction between irrelevant speech and irrelevant nonspeech was apparent.

The findings thus appear to have achieved the objective of the experiment, by uniquely endorsing one theoretical view (the Embedded-Processes model) while seeming to disconfirm the explanations afforded by competing theories. While the overall pattern of the data does

encourage this conclusion, it remains possible that a model may less adequately account for the observed pattern of dissociation (and non-dissociation), yet offer a specific explanation of individual irrelevant information effects that is still well-suited to address aspects of the data. Accordingly, a more detailed assessment of each model's position is certainly warranted, and is undertaken in the general discussion.

III.

EXPERIMENT II

In the first experiment it was shown that articulatory suppression effects are differentiated from irrelevant sound effects (speech and nonspeech) according to the influence they have on neural processing during a working memory task. An intriguing aspect of the time course data was that these differences appeared at distinct stages of the trial, with articulatory suppression effects emerging within the working memory network very early in the trial (during encoding), and irrelevant sound effects emerging later in the trial (as delay-based processing sets in). These temporal differences suggest a novel behavioral method for dissociating the effects of suppression and irrelevant sound by manipulating the specific timing of irrelevant information during the trial (e.g., by limiting irrelevant information to encoding only, delay only, or retrieval only). Accordingly, the main goal of the second experiment was to explore whether articulatory suppression and irrelevant sounds have different consequences to behavior when limited temporally to a particular stage of the working memory task trial.

Behavioral differences in the timing of articulatory suppression and irrelevant sound effects are suggested in the literature, though these differences have been largely overlooked. Six prior experiments have investigated the impact of “stage-limited” irrelevant speech on working memory (Hanley & Bakopoulou, 2003, Experiment 1; Macken, Mosdell, & Jones, 1999; Miles et al., 1991, Experiment 1, 2, & 3; Tolan & Tehan, 2002, Experiment 1). While these studies sought to investigate distinct theoretical issues, and therefore included additional manipulations, each of the experiments contained two relevant conditions: one in which irrelevant background speech occurred only during encoding (input), and another in which

irrelevant background speech occurred only during a delay period (rehearsal). Unfortunately, direct statistical contrasts between these two conditions were not reported in several of the experiments, thereby leaving it ambiguous whether a statistically significant difference was obtained. However, as shown in Table 3, there is a clear and consistent tendency for the irrelevant speech effect to be smaller when speech occurs during encoding, and larger when speech occurs during the delay. Experiment 2 of Miles et al. (1991) produced the only result inconsistent with this trend. The absence of any significant irrelevant speech effect (for either condition) in this experiment, however, led its authors to conclude that subjects may have adopted a visuospatial rehearsal strategy that confounded the data (responses were given on a spatially organized keypad). In the two other experiments of the same study, a significant effect of irrelevant speech was present, and the effect was largest for the delay condition. Indeed, Jones & Macken, (1993, p. 370) argue on the basis of this earlier finding that “any task that extends the period of rehearsal increases the opportunity for disruption to occur” (c.f. Larsen et al., 2000; LeCompte, 1994). While, the temporal specificity of irrelevant nonspeech effects has not been explored in a controlled comparison, results reported by Jones & Macken (1993, Experiment 5) suggest that nonspeech is likely to behave in a similar pattern to speech.

Both experiments 2 and 3 of Miles et al. (1991) also included a test of articulatory suppression effects at separate stages. In these experiments, articulatory suppression was found to be more damaging than irrelevant speech as is usually the case (e.g., Salamé & Baddeley, 1982). More relevantly, the pattern obtained for articulatory suppression was opposite to that obtained for irrelevant speech, with articulatory suppression effects being larger during encoding, and smaller during the delay (Table 3). The authors report that this apparent interaction between irrelevant information type (irrelevant speech, articulatory suppression) and

stage (encoding, delay) was not significant. However, the tested interaction included a third disruptive condition (irrelevant speech and articulatory suppression in combination) which may have diluted the interaction effect. Moreover, stage of interference was a between-subjects factor, raising some concern over the statistical power of the comparisons. No other published studies have examined the effects of articulatory suppression when limited to specific trial stages. However, preliminary work in our lab produced a consistent pattern of results, with articulatory suppression being most effectual when it occurs during the encoding period (Donovos, Chein, & Fiez, 2002).

The present experiment employs a delayed serial recall task in a procedure modeled on the work of Miles and colleagues (1991), with three relevant distinctions. First, the experiment includes conditions in which irrelevant nonspeech is deployed to disrupt memory. The inclusion of the nonspeech conditions allows for direct comparison of the temporal effects of irrelevant nonspeech to those of irrelevant speech and articulatory suppression. Second, for completeness, the experiment includes conditions in which the presence of each type of irrelevant information is limited to the retrieval period. Third, while stage of interference was a between-subjects factor in Miles et al., in the present study all manipulations were performed using a more statistically powerful within-subjects design.

If, as both the imaging results and trends in the literature suggest, articulatory suppression and irrelevant sound effects have their peak influence during separate temporal stages of the trial, it should be possible to demonstrate these differences as interactions in the within-subjects design. Whereas articulatory suppression effects are predicted to be greatest when suppression is required during the encoding period, irrelevant speech effects are predicted to be greatest when the background speech is isolated to the delay interval. Moreover, on the basis of the imaging

findings, it is predicted that irrelevant nonspeech will pattern with irrelevant speech, and thus also be most effectual during the delay.

Participants

Twenty introductory level psychology students from the University of Pittsburgh participated in the experiment in partial fulfillment of a course requirement. All subjects were tested individually, and reported normal hearing and normal, or corrected-to-normal, vision.

Design

The experiment employed a 3 x 3 factorial design with two within-subjects factors: irrelevant information type (articulatory suppression, irrelevant speech, irrelevant nonspeech) and stage of interference (encoding, delay, retrieval). In an additional control condition (quiet), performance was tested in the absence of irrelevant information. Subjects completed six trials from each cell, with trials sampled by random selection without replacement.

Stimuli

Both the to-be-remembered items and the stimuli used for irrelevant information were identical to those employed in Experiment 1, with the exception that the duration of the irrelevant sound sequences was shortened to 10 seconds to match each stage duration. Sounds were presented to participants through headphones at approximately 65dB (A), as measured by a digital sound level meter (Extech Instruments, Waltham, MA).

Procedure

Each subject participated in a one hour long experimental session in which they performed repeated trials of a delayed serial recall task. At the beginning of the session, subjects were given instructions about the possible nature and timing of irrelevant information in a given trial.

Subjects also completed a set of practice trials to ensure a clear understanding of the task demands (both subject's performance and self-report were used gauge readiness).

After the practice period, subjects completed six blocks of trials. Each block consisted of one trial from each of the experimental conditions. Trials were subject paced, and initiated by a keypress. The basic trial consisted of three stages: encoding, delay, and recall. Encoding included a 3.0s instruction event, followed by the presentation of a seven item list of to-be-remembered English consonants. List items were presented in the center of a computer monitor just above a fixation cross. Items appeared in random order on each trial, and were shown at a rate of one item per second (each item was shown for 0.8s, and separated by an interstimulus interval of 0.2s).

Following the presentation of the last list item, the prompt *wait* appeared on the screen, denoting the start of the delay interval. The delay interval lasted for 10 seconds. Subjects were instructed to covertly maintain the memoranda during this period. As in Experiment 1, subjects were directed not to employ intentional mnemonic "tricks" during the delay.

Retrieval was prompted by replacement of the delay period prompt with a graphic depicting a pen against a paper tablet. Subjects were instructed to respond to this recall prompt by immediately writing down as many of the to-be-remembered items as they could recall onto a provided response sheet. The response sheets contained seven boxes per trial, one for each TBR item. Subjects were required to recall the items in strictly forward order, leaving blank any boxes associated with items that could not be recalled, and attempting to place each remembered item in the box associated with its appropriate serial position. Responding was allowed for 10 seconds, following which time the recall prompt was removed from the display and an auditory cue signaling the end of the trial was heard through the headphones.

As in Experiment 1, a colored frame appeared around the stimulus display to signal the onset and offset of irrelevant information in each trial. The frame was color coded allowing subjects to determine which type of irrelevant information was being tested. The appearance and removal of the colored frame was synchronized to the start and end (respectively) of the stage in which irrelevant information was imposed (encoding, delay, or retrieval). On quiet trials, subjects were told to simply ignore the frame and continue performance of the basic delayed recall task. On irrelevant sound trials (speech and nonspeech), the onset and offset of the background sounds coincided with the onset and offset of the associated colored frame. Thus, the background sounds were presented specifically during the 10 second period associated with a given stage of the trial. Subjects were instructed to ignore the background sounds, and to focus on the working memory task. Sounds were heard through headphones worn by subjects throughout the duration of the experimental session. On articulatory suppression trials, subjects were required to initiate overt repetition of the word “*the*” at an approximate rate of two repetitions per second and as soon as the appropriately colored frame appeared around the display. Subjects were told to continue suppression at this rate until the frame disappeared from the screen (for a total duration of 10 seconds). All subjects were informed that their overt suppression was being recorded to ensure that the temporal boundaries of the suppression were tightly matched to the appropriate task stage, and to verify general compliance with the suppression instructions.

Results

Subjects’ responses were scored according to a strict serial recall criterion, wherein an item was considered correct only if it was written in the appropriate serial position. Typical serial position curves, with primacy and recency components, were obtained in each condition, suggesting that

the task engaged standard working memory processes. Data was pooled across serial positions, and a two-way (3x3) analysis of variance (ANOVA) was performed, with type of irrelevant information and stage of interference as within-subjects factors. The mean probability of correct recall for each of the experimental conditions is shown in Figure 7. The main effect of irrelevant information type was significant, $F(2,38)=22.41$, $p < 0.001$, with the effect driven by reduced overall performance under articulatory suppression (mean = 0.53) relative to the irrelevant speech and nonspeech conditions (means = 0.67 and 0.68, respectively). Stage also produced a significant main effect, $F(2, 38)=17.46$, $p < 0.001$, due to an increase in overall mean performance during recall (mean = 0.68) relative to encoding (mean = 0.63) and delay (mean = 0.57) conditions. Most importantly, the predicted interaction between irrelevant information type and stage was also observed [$F(4, 76)=14.22$, $p < 0.001$].

To further delineate the nature of this interaction, planned simple main effects analyses (one-way ANOVA's) and pair-wise contrasts were conducted. These tests indicated that the overall effect of stage was significant for each type of irrelevant information independently: articulatory suppression [$F(2, 59) = 12.49$, $p < 0.001$], irrelevant speech [$F(2,59)=3.37$, $p < 0.05$], and irrelevant nonspeech [$F(2,59) = 3.28$, $p < 0.05$]. Newman-Keuls *a posteriori* tests ($\alpha = 0.05$) further specified these simple main effects, and explained the irrelevant information type by stage interaction. For articulatory suppression, the Newman-Keuls test showed that the degree of impairment differed significantly at each stage, with suppression during encoding producing a larger impairment than during either delay or recall, and suppression during the delay also producing significantly more impairment than that during recall. In contrast, for both irrelevant speech and irrelevant nonspeech, only the pair-wise comparison between encoding and delay was significant, with *delay* producing the *greater* degree of impairment. Thus, the

significant interaction between irrelevant information type and stage is understood by recognizing that articulatory suppression is most damaging during encoding and less so during delay or recall, whereas the effects of irrelevant speech and nonspeech are weak during encoding and strong during the delay.

Comparison of each experimental condition to performance under the quiet (control) condition further clarifies the effects of stage-limited irrelevant information. When collapsed across stages, the data reveal typical and significant effects of articulatory suppression ($T(19)=9.14$, $p < 0.001$, one-tailed), irrelevant speech ($T(19)=3.45$, $p < 0.001$, one-tailed), and irrelevant nonspeech ($T(19)=3.57$, $p < 0.001$, one-tailed), relative to quiet trials. However, independent inspection of the irrelevant information effects at each stage shows that significant differences relative to quiet are not always obtained. Specifically, while articulatory suppression significantly impairs performance relative to quiet at all stages [encoding $T(19)=13.77$, $p < 0.001$; delay $T(19)=7.38$, $p < 0.001$; recall $T(19)=2.56$, $p < 0.05$], irrelevant speech and nonspeech differed significantly from quiet only in the delay condition [speech: encoding $T(19)=0.50$, $p = 0.63$; delay $T(19)=5.05$, $p < 0.001$; recall $T(19)=1.79$, $p = 0.09$; nonspeech: encoding $T(19)=0.24$, $p = 0.81$; delay $T(19)=6.50$, $p < 0.001$; recall $T(19)=1.47$, $p = 0.16$].

Discussion

The main objective of this experiment was to differentiate the articulatory suppression effect from irrelevant speech and nonspeech effects on the basis of their temporal specificity. Recall performance under stage-limited irrelevant information of each type showed precisely the expected pattern of dissociation, with articulatory suppression having its most damaging influence when it occurred during the encoding stage, and both irrelevant speech and nonspeech being most effectual when they occurred during the post-presentation delay. These findings

dovetail nicely with patterns observed in the fMRI data provided by Experiment 1 of this study, and demonstrate that trends apparent in the extant behavioral literature are statistically reliable when tested in a within-subjects paradigm. In addition, they extend the behavioral literature by characterizing the pattern of disruption produced by stage-limited irrelevant nonspeech, which had not been previously examined. Perhaps most intriguingly, the current behavioral experiment bolsters the results of the earlier imaging experiment (Experiment 1) in revealing a pattern of dissociation predicted only by the Embedded-Processes model, and not by the Phonological Loop, O-OER, or Feature models.

The clear similarities between the present findings and earlier behavioral work (especially Miles et al., 1991) are a further testament to the validity of the current experimental procedures. While the use of a within-subjects manipulation could potentially have encouraged participants to deploy unorthodox strategies when performing the working memory task, the observation of standard serial response curves in all conditions suggests that this was not the case. In further agreement with prior work, the overall disruption of articulatory suppression was found to be stronger than that produced by the other two irrelevant information types. When limited to only the delay period, however, the effects of all three irrelevant information conditions were approximately equated, a result that is again consistent (as evidenced by the mean effect size under delay only conditions shown in Table 3).

Of greatest importance to the aim of the present experiment was the detection of a statistically significant interaction between type of irrelevant information and stage of interference (Figure 7). This interaction resulted from strong effects of articulatory suppression during encoding that were reduced in later stages (delay, recall), as compared to small effects of irrelevant sound during encoding that became larger during the delay (and were intermediate in

size during recall). While the direction of the interaction was precisely as predicted on the basis of earlier behavioral findings, one inconsistency between the present and earlier work deserves further attention. Specifically, the interaction between irrelevant information type and stage was driven in part by notably weak effects in the encoding-only irrelevant sound (speech and nonspeech) conditions.

The absence of a statistical difference for encoding-only irrelevant speech relative to the quiet working memory control is, however, in apparent conflict with some previous studies wherein the same manipulation (irrelevant speech during encoding only) was found to produce small but statistically significant disruptions (Miles et al., 1991; Tolan & Tehan, 2002). Interestingly, those studies reporting a significant encoding-only irrelevant speech effect employed either a slower presentation rate (Miles et al., 1991) or longer TBR lists (Tolan & Tehan, 2002) such that the total duration of encoding was slightly longer than in the present study. If we adopt a common assumption that active maintenance (e.g., rehearsal) can begin before the end of the encoding period, and further assume that irrelevant sounds act principally on these maintenance processes (as argued by Miles et al., 1991), then the apparent discrepancy is explained. Namely, the more the context of the experiment allows active maintenance to take place during the “encoding” period (e.g., by lengthening the encoding period, or allowing more time between arriving items), the more susceptible performance will be to interference from irrelevant sounds. Direct evidence that this is the case comes from Macken et al. (1999), wherein irrelevant speech was presented in discrete sub-stages of the working memory trial. The most pertinent finding from this study was that irrelevant speech presented during the first five seconds of a ten second encoding period had a negligible effect, while irrelevant speech presented during the latter 5 seconds of encoding had a substantial, and statistically significant,

effect. Of further interest, their study found that strong effects of irrelevant speech persisted for the early half (first five seconds) of the ensuing delay interval, but began to weaken in the latter half of the delay. This observation fits nicely with the imaging data from Experiment 1, in which the neural effect of irrelevant sound was similarly weakened in the latter half of the delay.

Neither the imaging data from Experiment 1 (wherein irrelevant information was terminated prior to recall) nor previous behavioral studies supported strong predictions for the effect of recall-only interference. However, in one prior study experiment (Miles et al., 1991, Experiment 1), recall-only irrelevant speech was shown to have a negligible affect on performance. On the basis of the imaging data from Experiment 1, it could be further expected that whatever the effect of irrelevant speech, it would be mimicked by irrelevant nonspeech. Consistently, when limited to the recall stage, both types of irrelevant sound failed to statistically alter performance. The expected consequence for recall-only articulatory suppression was somewhat less clear, but earlier behavioral findings (e.g., Baddeley et al., 1984) intimated that there might be an observable effect. In the present study, a statistical effect of recall-only articulatory suppression was found. However, the disruption produced in this condition was small and did not differ statistically from the disruptions produced by comparable irrelevant sound conditions. Given these non-differences, appropriate interpretation of this aspect of the results is equivocal.

In summary, the results of this experiment demonstrate a clear dissociation in the temporal specificity of articulatory suppression and irrelevant sound effects, while also showing equivalent temporal specificity for irrelevant speech and irrelevant nonspeech. Accordingly, the results corroborate the neuroimaging evidence from Experiment 1, and lend further backing to only the Embedded-Processes account of irrelevant information effects. The present observation

of comparable delay-only articulatory suppression and irrelevant sound effects does however beg the question of whether articulatory suppression and irrelevant sound effects might have a common action on delay-period processing, while only articulatory suppression involves a mechanism that is additionally disruptive to encoding processes. Such an account may allow alternative theories (e.g., Phonological Loop, O-OER) to escape contradiction from the present findings. In the general discussion that follows, the merits and faults of taking these alternative perspectives are further addressed.

IV.

GENERAL DISCUSSION

Considered together, the two experiments in this series provide convergent evidence regarding the functional equivalence, and non-equivalence, of the three irrelevant information effects. Specifically, both the neuroimaging evidence from Experiment 1, and the complementary behavioral findings from Experiment 2, point toward a dissociation of the articulatory suppression effect from the functionally equivalent effects of irrelevant speech and irrelevant nonspeech. Leverage in understanding the basis for this global pattern of dissociation is afforded by a further point of consistency across the two experiments, the relative timing of interference produced by each irrelevant information type. In particular, both experiments indicate the same temporal dissociation of the effects, with articulatory suppression having its greatest influence on working memory at the beginning of each trial (encoding) and the irrelevant sound effects having their greatest impact during the post-presentation delay interval.

Implications for Working Memory Theory

Four competing theories of working memory, each widely applied to address the effects of irrelevant information, were detailed in the introduction. It was argued that the differential predictions afforded by each theory could be exploited as a way to adjudicate between their alternative accounts. Indeed, the coherent pattern of results produced in the two above experiments appear to endorse specifically the account provided by the Embedded-Processes model, while presenting a challenge to interpretation under the Phonological Loop, O-OER, and Feature models. However, an important evaluative step must still be undertaken before we can

reasonable grant this endorsement. Namely, while the global dissociation pattern is nicely addressed within the Embedded-Processes framework, it has yet to be demonstrated that the particular mechanisms it proposes can be readily applied to explain the obtained data (for instance, the model may prove unable to account for relative differences in temporal susceptibility to each information type). In the same vein, an alternative model that encounters difficulty with the overall dissociation pattern may provide a suitable mechanistic account for a given effect. Accordingly, the specific handling of evidence for each irrelevant information effect must still be considered to determine the viability of alternative views.

The Phonological Loop

The Phonological Loop assumes that articulatory suppression effects can be explained as a loading of the articulatory resources normally engaged by rehearsal. This loading has two important consequences in that it first blocks the conversion of visual stimuli into phonological form, and second prevents active maintenance via subvocal rehearsal.

In Baddeley's multiple-component model (e.g. Baddeley, 1986; Baddeley & Logie, 1999), preventing visual memoranda from attaining a phonological form will deny access to the phonological store and force the employment of an alternative maintenance system that is sub-optimal for the retention of verbal information (e.g., the visuospatial sketchpad). Accordingly, the blocking of a phonological conversion process seems at first to provide a plausible explanation for the observation that articulatory suppression is highly disruptive in the encoding stage (Experiment 2), and that it enhances neural activity principally during this period (Experiment 1). At least two difficulties, however, are encountered by this view. The first comes from evidence in the behavioral literature that articulatory suppression performed throughout the trial is of comparable size for both visual and auditory modalities of presentation

(Peterson & Johnson, 1971). Such results run counter to the necessary prediction that a smaller effect should be obtained with auditory presentation, since such conditions obviate the putatively disrupted phonological conversion process. The second shortcoming is based on the present neuroimaging data (Experiment 1). If, as presumed by Baddeley's multiple-component view, articulatory suppression prevents phonological coding and forces the abandonment of the phonological loop, then a corresponding drop-out of regions associated with phonological loop processes should be observed (while "rehearsal" areas may remain active because they are engaged by silent articulation, at least the neural correlates of the phonological store should exhibit reduced activation under suppression). The imaging findings do not substantiate this position, and instead show that concurrent articulatory suppression trials produce activation in all of the regions engaged for quiet working memory.

A related difficulty is encountered in the assumption that articulatory suppression disrupts rehearsal during the delay (at least as explained in the context of the Phonological Loop). Delay-only suppression should allow stimuli to be properly registered into the store,⁸ but then block rehearsal during the subsequent retention period. Without rehearsal to continuously refresh decaying information, there should be a catastrophic loss of information (the lifetime of a phonological trace without reactivation is estimated at 2 seconds; Baddeley, 1986). However, delay-only articulatory suppression was found to have a relatively reduced effect (compared to suppression at encoding, Experiment 2).

As described in the introduction, two alternative explanations for irrelevant sound effects have also been derived from the phonological loop model. The first, based on Salamé & Baddeley's initial formulation, assumes that irrelevant speech effects stem from confusions in

⁸ It should be noted that subjects had no foreknowledge of the timing or type of interference, and would accordingly be expected to have used typical maintenance strategies until the onset of articulatory suppression.

the verbally-specific phonological store, while irrelevant nonspeech effects occur elsewhere (perhaps due to dual-task context). The more recent view, proposed by Larsen & Baddeley (2003), contends that irrelevant speech effects stem not from confusions in the store, but from disruption of the seriation processes that operate within the store. The irrelevant nonspeech effect is not formally addressed by this newer proposal. With respect to the present data, the earlier view has obvious difficulty in that it predicts dissociation between irrelevant speech and irrelevant nonspeech effects within the working memory network. While the second account (Larsen & Baddeley, 2003) is less clear on the separability of irrelevant speech and nonspeech, its commitment to explaining irrelevant speech effects as taking place within the verbally-specific phonological store seems to necessitate the same theoretical predicament.

Thus, while Baddeley (2000) acknowledges difficulties associated with the original view provided by Salamé and Baddeley, and has recently constructed a revised account, neither seems to plausibly explain the present pattern of findings regarding the irrelevant sound effects. Taken together with the difficulties encountered by this model in its handling of the articulatory suppression effect, and with the general pattern of dissociation between irrelevant speech and nonspeech, the evidence seems stacked against the Phonological Loop account.

The O-OER model

The position advocated by the O-OER model is that all three interference manipulations - articulatory suppression, irrelevant speech, and irrelevant nonspeech – produce a disruptive effect on the process of seriation that is normally employed to record and maintain the order in which memorial information arrives to the system. The position that these effects have a common source seems to be at odds with the present dissociation of articulatory suppression from irrelevant sound effects. For example, the assumption of functional equivalence provides

no means to explain the directionally opposed activity changes for articulatory suppression and irrelevant speech that were exhibited in Experiment 1. Once again, however, it is worth evaluating the proposed mechanism of interference, disruption of seriation, in its own right.

Jones and colleagues contend that irrelevant sounds, and the act of (covertly) articulating a speech token as required during concurrent articulatory suppression, create novel streams of objects in memory whose pointers interfere with those of the memorial stream. As noted above, such streaming of the articulatory token(s) is predicted principally when there is variation in the repeated sequence. Given that substantial articulatory suppression effects were obtained in the current study with a single repeated speech token, it is not clear if the O-OER model provides an explanation of the basic behavioral effects (Experiment 1 & 2). Although Jones and Macken (2003; Macken & Jones, 1995) propose that articulatory suppression may also have a “vocalization” effect that is separate from the “changing-state” effect embodied in their model, the absence of any overt articulatory gestures in Experiment 1 of this study discounts this additional source of disruption as an explanatory factor. Thus, to proceed with an evaluation of the model’s claims, we must allow that the articulatory stream varied sufficiently to produce a changing-state effect.

A basic claim of the O-OER model is that representations in memory are generated whenever changing-state stimuli are presented in the auditory modality (irrelevant speech and nonspeech) or have been subvocally articulated (memory items, silent articulations). It can be inferred from this view that all mnemonic and non-mnemonic conditions in the neuroimaging study (Experiment 1) should yield corresponding delay-based activations in a region associated with seriation, since all conditions would accordingly generate pointers in memory. No region exhibited such universal activation. Gisselegard and colleagues (2003) suggest that the seriation

process may be housed in the anterior left superior temporal region, where they observed activity reductions due to irrelevant speech. Experiment 1 failed to replicate this earlier finding, and as argued above, this region is not typically observed as part of the verbal working memory network (e.g., Cabeza & Nyberg, 2000, though it may have an important role in language processing as suggested by Gisselegard et al., 2003; Fiez et al., 1996).

Perhaps more direct evidence for a specific seriation mechanism in working memory is afforded by neuroimaging studies explicitly manipulating the requirement to maintain serial order. Two such studies have been reported to date, Marchuetz et al. (Marchuetz, Smith, Jonides, DeGutis, & Chenevert, 2000) and Henson et al. (Henson, Burgess, & Frith, 2000). The consistent finding across these two studies is that the superior parietal cortex seems to be more active when task conditions demand the maintenance of serial order as compared to non-serial memory conditions. A right superior parietal activation was also observed in Experiment 1. This region was modestly engaged for all working memory conditions, but activation was specifically limited to the encoding period. Moreover, the region showed no modulation by irrelevant information. Thus, while the superior parietal cortex may play an important role in sequencing the information presented at encoding, it does not appear to contribute to the iterative and ongoing “threading” process assumed to be influenced by irrelevant information according to the O-OER model.

Disruption of seriation does not seem to provide a sufficient account of irrelevant information effects in the imaging data from Experiment 1. It may however provide a reasonable account for the temporal specificity of effects observed in Experiment 2. As mentioned in the introduction to the model, it is assumed that the episodic pointers between items become stronger each time the stream is traversed, or “threaded.” Since the pointers in the

memorial stream become stronger as the trial proceeds, threading thus becomes less susceptible to disruption from pointers in the irrelevant processing stream. Consequently, disruption of the seriation process during encoding would have a stronger effect than would disruption later in the trial. This explanation provides a perfectly acceptable account of the articulatory suppression data obtained in Experiment 2, wherein articulatory suppression was highly effectual in the encoding-only period, and less so later in the trial. However, the same account also predicts monotonic effect-size reductions (across stages) for the irrelevant sound conditions. Experiment 2 demonstrates that this prediction is not born out, since rather than decreasing in magnitude in the delay-only condition, the size of irrelevant sound effects were largest in the this condition.

Interestingly, a different position afforded by the O-OER model could be applied to explain this alternative pattern obtained for irrelevant sound effects. This position was also considered in the discussion section of Experiment 2, and regards the notion that irrelevant information acts principally on maintenance, rather than encoding, processes (e.g., Miles et al., 1991). By this view, rather than becoming weaker in the delay period, the effects of irrelevant information should become stronger because maintenance processes are more heavily engaged. Once again, the dilemma for the O-OER model is that while this position reasonably explains the irrelevant sound data, it cannot simultaneously address the articulatory suppression results.

The Feature Model

Like the O-OER model, the Feature model predicted that both articulatory suppression and irrelevant speech would produce a similar effect on neural processing. In addition, the model predicted a dissociation of irrelevant speech from irrelevant nonspeech. Given that neither the expected similarity between suppression and irrelevant speech, nor the expected difference between irrelevant speech and irrelevant nonspeech was present in the data, it could be argued

that the Feature Model account of interference effects is the least compatible with the overall results. Still, the basic position of the model that certain disruptions of memory stem from a retroactive interference process does seem defensible.

Both articulatory suppression and irrelevant speech effects are explained in the Feature model as the result of “feature-adoption,” a form of retroactive interference whereby features of the irrelevant information are imposed upon memorial item traces. It is not clear whether such retroactive interference should produce an increase, or a decrease, in the fMRI signal of regions where primary memory traces are formed and maintained. However, it is implausible that the direction of activity modulation, if caused by a common process, should vary depending on the particular interfering material. Accordingly, the assumption of a common mechanism provides no explanation for the directionally opposed activity changes produced by articulatory suppression (activity enhancing) and irrelevant speech (activity reducing). In other words, while we cannot rule out feature-adoption as a suitable explanation for one of the two effects, we can reasonably conclude that it does not explain both.

Since retroactive interference in the Feature model occurs upon the entry of a novel trace into primary memory, concurrent irrelevant information must itself be encoded as a trace in order to interfere with to-be-remembered items. On purely intuitive grounds, it seems that the intentional articulatory acts associated with suppression would be more likely to generate memory traces than the purposefully ignored constituents of irrelevant speech. In Experiment 1, significant activation of the left precentral gyrus and right cerebellum were found in non-mnemonic silent articulation trials, and although highly speculative, these activations could be construed as evidence of trace formation. If it is further assumed that the result of interference from feature-adoption is to amplify fMRI signal, then a reasonably coherent account of the

increases observed during concurrent articulatory suppression trials in Experiment 1 can also be constructed (though the model provides very few guidelines by which to assess the appropriate neuroanatomical localization or distribution of these increases).

Specific assumptions about the nature of feature-adoption help to further evaluate this account of articulatory suppression effects. As characterized by Nairne (1990), interference caused by feature-adoption can only occur between temporally successive memory traces. That is, when a new trace is formed in primary memory it can cause overwriting of only the previously formed trace. This assumption provides the Feature model with a way to explain the observation of a strong articulatory suppression effect during encoding-only conditions (Experiment 2), and the corresponding temporal specificity of its neural consequences (Experiment 1), because primary memory traces for both TBR and irrelevant items are being formed during encoding. A difficulty encountered by this account, however, is that it offers no way to explain the additionally significant effects of delay-only articulatory suppression. In adapting the Feature model to address “retroactive” (i.e. delay-only) effects of irrelevant speech, Neath (2000) introduced a necessary additional assumption. Specifically, that memorial and irrelevant item traces could be made successive in memory during the post-presentation delay period by virtue of rehearsal. Even with this additional assumption of rehearsal, the observation of delay-only articulatory suppression effects (Experiment 2) can only be explained if it is still further assumed that articulatory suppression does not itself disrupt the proposed rehearsal process (if it did, irrelevant and memorial items would never be temporally coincident during the delay). Under the somewhat awkward resulting account, moderate delay-only articulatory suppression effects can be explained by assuming that each irrelevant utterance occasionally follows a rehearsal of a memorial item, and thus produces retroactive interference. Although

originally intended to explain irrelevant speech effects, these same set of assumptions are unable to account for relatively smaller effects of encoding-only, as compared to larger delay-only, irrelevant speech.

Before departing from the Feature Model account, we can briefly consider its position regarding irrelevant nonspeech. Since nonspeech traces are assumed to be incapable of interfering specifically with the features of memorial items, the effect of irrelevant nonspeech must have a distinct origin. It is tentatively proposed that the imposition of a dual-task context is the basis for the effect. While it seems uncontroversial that some additional demand is created by the presence of irrelevant information (of any kind), there is an interesting incompatibility between this dual-task account and the imaging data. In particular, dual-tasking is normally evidenced in imaging studies as an increase in regional activity, particularly in executive frontal areas (e.g., dorsolateral prefrontal) thought to mediate processing of the two tasks (e.g., D'Esposito et al., 1995). However, the present study shows that rather than increasing activity, the presence of irrelevant sounds (speech and nonspeech) causes a moderate reduction in working memory activity, and has no specific effect on executive frontal areas. Accordingly, the findings suggest that the need to ignore irrelevant sound does not itself constitute a secondary task.

The Embedded-Processes Model

The perspective afforded by the Embedded-Processes model to address the effects of irrelevant information on working memory proved most amenable to the overall pattern of data obtained from both fMRI and behavioral experiments. Specifically, the model accurately predicts the dissociation of articulatory suppression from the two irrelevant sound effects, and the functional equivalence of irrelevant speech and irrelevant nonspeech. However, while the attentional

account provided to explain irrelevant sound effects is unique to the Embedded-Processes view, its handling of the articulatory suppression effect borrows from the accounts provided by other models (particularly the Phonological Loop). Accordingly, some of the difficulties encountered by competing theories might be expected to prove similarly problematic for the Embedded-Processes account.

The Embedded-Processes model seems most committed to the view that the effect of articulatory suppression is explainable as the result of loading on articulatory resources (as in the Phonological Loop, see Cowan, 2001). As discussed above, such loading is thought to block phonological conversion, and somewhat more importantly, to prevent subvocal rehearsal from refreshing fading representations in memory. However, by providing attentional scanning as an explicit strategic alternative to subvocal rehearsal, the model yields a somewhat different explanation for the present findings. In particular, while articulatory suppression may block subvocal rehearsal, attentional scanning can serve an alternative means for retaining information encoded into memory (though attentional scanning is presumably a less effective way to sustain serial information).

One benefit of this position is that it can explain the persistence of activity in all working memory areas even under suppression (Experiment 1), a finding that proved challenging to address in the Phonological Loop. Specifically, regions normally involved in rehearsal may remain engaged under articulatory suppression to control the articulatory gestures associated with suppression, while regions associated with item representation (storage) remain active by virtue of the sustaining influence of attentional scanning. In accepting this alternative account, however, it must be assumed that information is registered into sustainable portions of memory despite blocking of the phonological conversion process. This position is reasonable within the

Embedded-Processes framework in that the model does not posit a phonological store dedicated to the maintenance of verbal information, and instead assumes that all features of an item (phonological and non-phonological) are activated together in a distributed long-term memory.

Reactivation provided by attentional scanning also explains a second finding that proved challenging to the Phonological Loop account – that delay-only articulatory suppression produces only a moderate loss of memorial information (Experiment 2). Within the Embedded-Processes framework, this finding can be addressed by assuming that while rehearsal is blocked by suppression, performance can be sustained to an intermediate extent through reactivation provided by attentional scanning. A further prediction that emerges from this account is that articulatory suppression should increase activity in regions associated with attentional scanning, since such processes are presumed to compensate for the loss of rehearsal. Indeed, increases in inferior parietal activity observed with concurrent articulatory suppression trials are commensurate with this prediction (discussed in further detail below).

As described thus far, the alternative provisions of the Embedded-Processes model address some findings that challenged the Phonological Loop account, despite adoption of a similar view on articulatory suppression. However, in dispensing with the assumption that preventing the phonological conversion process blocks entry into working memory, the strong influence of articulatory suppression during encoding-only conditions remains to be explained. This finding can be addressed within the Embedded-Processes framework by assuming that subvocal rehearsal becomes progressively automated during the encoding and early delay period, and thus more robust to disruption from articulatory suppression (Cowan, 2001; Naveh Benjamin & Jonides, 1984 – this possibility has also been suggested by Baddeley, 1986). As explained by Cowan (2001), this automation takes place as subvocal rehearsal becomes sustainable outside of

the focus of attention (which he assumes is important in establishing the rehearsal program). Accordingly, the “critical period” of articulatory suppression may be limited to the earlier portion of the trial when rehearsal is most susceptible to disruption. While not explicit in Cowan’s description, it must be further assumed that the automation of rehearsal is not complete before the delay begins, since there would otherwise remain an erroneous prediction that delay-only articulatory suppression should have no effect on recall performance.

The Embedded-Processes model offers a distinct explanation for the effects of irrelevant speech and nonspeech, which are thought to arise from a type of attentional distraction. In distinguishing the irrelevant sound effects from that of articulatory suppression, this view circumvents the difficulty encountered by other models (O-OER, Feature) in explaining directionally opposed signal changes across irrelevant information types. The specific account of irrelevant sound effects stems from the assumption that attention participates in the active maintenance of items in memory, via attentional scanning. Decreases in regional activity (particularly inferior frontal regions) under these conditions can thus be interpreted as reflecting the loss of representational information (e.g., phonological) when the retentive benefits of attentional scanning are removed (or disturbed). While similar representational loss would be expected with articulatory suppression, associated decreases in memorial representation may be masked by the additional need to maintain and generate irrelevant utterances.

The results of Experiment 2, showing weak effects of irrelevant sound during encoding-only interference, and strong effects during delay-only interference can also be reasonably addressed within the Embedded-Processes account. Two factors may limit the effect of interference from irrelevant sounds during encoding. First, the physical presence of memorial stimuli during encoding may be sufficient to hold the focus of attention in place, and thus

prevent orienting toward irrelevant stimuli. Second, strong initial activation at encoding may allow item representations to endure through brief periods of attentional distraction. In contrast, once the delay period commences, memorial stimuli are no longer physically present, and their representations are likely to drop below initial levels of activation (despite covert maintenance processes). Accordingly, delay-only irrelevant sounds may be most disruptive because attention is more susceptible to being drawn off during this period, and such attentional distraction will have a more damaging effect on item retention by allowing representations to fall below recoverable levels of activation.

It was argued at the onset of this discussion that the Embedded-Processes model most readily explains the overall pattern of dissociation found across the two present experiments. Importantly, the current assessment demonstrates that the model also supports meaningful interpretation of the observed articulatory suppression, irrelevant speech, and irrelevant nonspeech patterns independently.

A Revised Neuroanatomical Mapping of Working Memory Processes

Prior neuroimaging research has shown that it is possible to adopt the perspective of Baddeley's multiple-component model and to corroborate many of its predictions. The prevailing view of how working memory processes map onto specific brain structures has been derived from this earlier work. The results of the present study, however, seem to resist interpretation under the Phonological Loop hypothesis, and thus add to a growing body of evidence that challenges the prevailing neuroanatomical mapping (see also Chein & Fiez, 2001; Chein, Ravizza, & Fiez, 2002; Ravizza et al., in press). The present data suggest instead that a mapping of theory to brain based on the Embedded-Processes model may prove more accurate. To support future testing of novel predictions based on this alternative theory, a revised neuroanatomical theory of working

memory processing is needed. While the available data does not fully constrain a revised model, the rudiments of an alternative mapping can be constructed from Cowan's (1995, 1999) speculations on the probable neural substrates of working memory, and from the available neuroimaging evidence (Figure 8).

The resulting neuroanatomical theory assigns regions activated by a working memory task to one of three sources – executive processing, covert maintenance, or active memory. Executive processes are assumed to be housed in frontal areas, especially the dorsolateral prefrontal cortex (Cowan, 1995, the same is normally assumed about the executive system of Baddeley's model). To support covert maintenance in verbal working memory, both attentional scanning and subvocal rehearsal areas may be recruited. Cowan (1995) assumes that the inferior parietal cortex is the neural substrate for the focus of attention. Accordingly, attentional scanning may be mediated by parietal shifting of the attentional focus. Attribution of this attentional function to the inferior parietal cortex is highly consistent with the broader literature (e.g. Corbetta & Shulman, 2002), but represents an important departure from the prevailing working memory theory, which holds this region to be the site of phonological storage. Data from the present paper can also be construed as support for this reinterpretation. Specifically, increased inferior parietal activity during articulatory suppression can be interpreted as reflecting an increased demand on attentional scanning when subvocal rehearsal is disrupted. Likewise, modest (nonsignificant) reductions of activity in this region during irrelevant sound trials may reflect strategic inhibition of the attentional scanning process to limit the effect of the distracting irrelevant sounds when subvocal rehearsal is possible.

The Embedded-Processes model provides few constraints on the appropriate localization of the rehearsal process. However, an assumption used earlier to explain the temporal specificity

of articulatory suppression effects in the context of this model can be similarly employed to inform a speculative mapping of the rehearsal process. The relevant assumption is that rehearsal should be conceptualized as a dynamic multi-staged process, wherein the rehearsal sequence becomes more stable (automatic) in later stages (see e.g., Naveh-Benjamin & Jonides, 1984, Chein & Fiez, 2001). Accordingly, regions exhibiting only transient contributions at the onset of each working memory trial may be thought to make essential contributions to rehearsal by supporting the “set-up” stage, while regions showing sustained delay-related activity may be thought to mediate automatic aspects of rehearsal. By this account, cerebellar and dorsal inferior frontal regions, both found to exhibit transient activity, may support the early stage of rehearsal by retrieving and assembling the motoric plans that will comprise the final rehearsal sequence. Similarly, as suggested by Cowan (2001), the focus of attention may also be engaged to initiate rehearsal, thus explaining transient parietal contributions. Meanwhile, the final rehearsal sequence may become stabilized, and hence sustained, within premotor and pre-supplementary motor areas, both found to exhibit significant activity throughout the trial.

While previous research has treated Broca’s area as the most likely site of subvocal rehearsal (e.g., Awh et al., 1996; Henson, 2001; Paulesu et al., 1993; Smith & Jonides, 1999), my colleagues and I have suggested that at least the ventral portions of this region may be more appropriately interpreted as a site of representation for novel phonological sequences (see below and (Chein et al., 2003). This interpretation is consistent with Cowan’s (1995) more general assumptions regarding the nature of active memory. Specifically, representations of existing knowledge are assumed to be distributed throughout the neocortex. When external stimuli or internal processes activate a given memory representation, the particular activated (encoded) features determine where in the cortex this active representation is processed and preserved. For

sensory features, activated areas are assumed to be the same as, or adjacent to, the brain areas involved in perceiving a stimulus (i.e. primary sensory cortex). In contrast, non-sensory features (e.g., semantic, phonological) are likely to be represented in association cortices. In verbal maintenance tasks, activated memory representations are likely generated or contained within ventral inferior frontal areas (e.g., Broca's area and the adjacent insular cortex). Thus, Broca's area may serve not as the site of rehearsal, but as a general source of phonological representation and processing that becomes active when a phonological sequence of to-be-remembered items is presented.

Conclusions

As proponents of the prevailing theoretical view of working memory now construe neuroimaging findings as confirmatory of their position (see e.g., Baddeley, 2000; Larsen & Baddeley, 2003), there is a real danger that the ability and motivation to advance alternative theories will diminish. In demonstrating that other models can be reasonably tested through neuroimaging, the present experiment thus has important implications for both the future of neuroimaging research and working memory theory alike. Perhaps of even greater significance, the obtained results do not lend support to the prevailing view, and instead appear to advocate an alternative "attentional" theory of working memory embodied by the Embedded-Processes model. Specifically, the two experiments of this study confirm the predictions of only the latter theory that the effect of articulatory suppression is dissociated from those of irrelevant sound, while irrelevant speech and nonspeech effects are equated.

By providing novel constraints on theory, based on the neuroanatomical and temporal specificity of irrelevant information effects, the present data demonstrates that certain theoretical account must be either reconsidered or abandoned. The evidence should not, however, be

construed as damning to any theory as a whole, since revision to correctly address the present evidence is possible within each of the considered theories. For the Phonological Loop, revision could begin with a reassessment of whether the effects of irrelevant nonspeech could occur within the phonological store in a manner similar to irrelevant speech effects. For the O-OER model, elaboration of the additional factors, beyond changing-state, by which articulatory suppression acts on memory (e.g., “vocalization”) may be a productive line of revision. Within the Feature model, a rethinking of the position that irrelevant speech occurs by the same feature-adoption process as does the articulatory suppression effect could both address the current data as well as concerns over prior empirical evidence used to defend this position. However, it should be underscored that for any of these theories, such revisions would provoke a “cascade” of further theoretical revisions, since the accounts provided by each theory to address the effects of irrelevant information are deeply intertwined with their handling of other behavioral phenomena.

In this regard, it can be hoped that the neuroimaging data provided by the present study on the effects of articulatory suppression, irrelevant speech, and irrelevant nonspeech can be considered in combination with the data from Chein & Fiez (2001), wherein word-length, phonological similarity, and lexicality were examined, to help inform the direction of theoretical revision. Taken together, these studies provide neuroimaging data regarding several of the major behavioral phenomena that must be addressed in a successful theory of working memory. Moreover, the present work demonstrates how the cognitive neuroscientific approach, combining neuroanatomical (neuroimaging) and behavioral evidence to constrain theoretical development, can help to move a currently fractionated theoretical literature toward a consensus view of the nature of working memory. Accordingly, while further studies are clearly needed to evaluate

specific concepts in working memory (e.g., the Embedded-Processes model and the revised neuroanatomical mapping of working memory function derived from it), it is hoped that the present research will provide a vital foundation for the design and interpretation of future work.

Figure Captions

Figure 1. Competing theories of working memory used to explain the irrelevant information effects. (A) The distinct patterns of dissociation predicted by four competing theories of working memory, and the main structural and processing components of the (B) multiple-component model (adapted from Baddeley, 1986), (C) O-OER model (adapted from Jones, 1996), (D) Feature model (adapted from Nairne, 2002), and (E) Embedded-Processes model (adapted from Cowan, 1999).

Figure 2. The neuroanatomy of working memory and a mapping of the distribution of function according to the prevailing view. (A) The network of regions consistently implicated in neuroimaging studies of verbal working memory. This network is comprised of the dorsolateral prefrontal cortex (DLPFC), the ventrolateral prefrontal cortex (VLPFC), the premotor cortex, the pre-supplementary motor area (pre-SMA), the anterior cingulate cortex (ACC), and the cerebellum. (B) The prevailing interpretation of regional function based on the phonological loop of Baddeley's multiple-component model.

Figure 3. Schematic diagram of the experimental protocol used in Experiment 1. (Top) Display sequence for working memory and non-mnemonic trials. (Middle) Timing of irrelevant information relative to the stages comprising each trial (encoding, delay, recall, rest). (Bottom) The four covariates used in analysis of encoding (e), delay (d1 and d2), and recall (r) stages.

Figure 4. The effects of irrelevant information on probed recall accuracy in Experiment 1. Statistically significant decrements in accuracy were present for each of the irrelevant information conditions relative to quiet.

Figure 5. Quiet working memory regions and their activation profiles in Experiment 1. Voxels shown as active surpassed a false discovery rate threshold of 0.01 in the group composite data for the early delay covariate (d1), late delay covariate (d2), or both. The statistical images are shown overlaid onto horizontal sections of the reference structural image at +40mm, +25mm, +5mm, and -25mm from the anterior commissure to posterior commissure plane. Activation profiles under each working memory condition are shown (counterclockwise from top left) for the pre-SMA (BA 6), left dorsolateral prefrontal (BA 46), left anterior insula (BA 45/13), left ventral inferior frontal (BA 45/44), right cerebellum, left basal ganglia, left dorsal inferior frontal (BA 44/9), and left premotor areas.

Figure 6. Activation profiles for regions “recruited” by concurrent articulatory suppression trials. Patterns of activity during working memory trials are shown for averaged bilateral anterior middle frontal (BA 46/10), averaged bilateral inferior parietal (BA 40/39).

Figure 7. Delayed serial recall task performance under stage-limited irrelevant information in Experiment 2. Average accuracy (pooled across subjects and serial positions) is shown for quiet, articulatory suppression, irrelevant speech, and irrelevant nonspeech conditions when limited temporally to the encoding, delay, or recall stages. A significant interaction between irrelevant information type and stage of interference was obtained.

Figure 8. A revised neuroanatomical model of working memory based on the Embedded-Processes Framework.

Table 1

Local maxima of regions showing significant activity during encoding, delay, and recall periods in quiet working memory trials

	Encoding (e)				Early Delay (d1)				Late Delay (d2)				Recall (r)			
Delay-Period Activations	P	x	y	z	P	x	y	z	P	x	y	z	P	x	y	z
Medial Frontal (BA 6/32)	ns				**	-8	9	41	**	-8	15	42	***	-8	5	41
L Precentral (BA 6)	***	-49	-8	38	***	-46	-9	38	**	-49	-10	39	***	-54	-5	31
R Precentral (BA 6)	*	39	1	23	**	50	-11	34	ns				*	47	1	25
Anterior Cingulate (BA 24/32)	ns				**	11	12	27	*	12	19	25	*	7	11	34
L Precentral/Inferior Fr (BA 6/9)	ns				ns				***	-32	9	33	ns			
L Inferior Frontal (BA 44/9)	**	-43	4	24	**	-45	1	24	ns				***	51	6	18
L Middle Frontal (BA 46)	ns				ns				*	-50	25	25	*	-40	38	19
L Inferior Fr (BA 45/44)	*				**	-40	11	8	**	-43	19	12	***	-37	11	9
L Basal Ganglia (Putamen)	ns				***	-22	2	17	ns				***	-19	5	5
R Basal Ganglia (Putamen)	ns				**	15	0	8	ns				***	12	5	4
L Ant Ins (BA 13/45)	ns				***	-29	27	7	**	-31	27	7	**	-32	23	6
R Ant Ins (BA 13/45)	ns				**	29	21	7	**	29	18	2	*	36	17	1
L Post Middle Temporal (BA 21)	ns				*	-42	-51	5	ns				ns			
L Middle Temporal (BA 21)	ns				ns				**	-58	-34	1	ns			
R Cb	**	39	-53	-24	*	36	-62	-23	ns				ns			
L Cb	*	-46	-65	-27	**	-44	-59	-27	ns				*	-43	-56	-27
Encoding & Recall Activations																
R Sup Par/Intraparietal (BA 7/40)	*	24	-64	44	ns				ns				*	35	-49	49
L Pre/Postcentral (BA 4/3/2)	ns				ns				ns				***	-33	-25	48
R Precentral (BA 4/6)	ns				ns				ns				***	26	-6	47
L Inferior Parietal (BA 39/40)	*	-26	-74	26	ns				ns				***	-31	-51	42
R Inf Parietal (BA 39/40)	*	24	-69	29	ns				ns				ns			
L Ant Middle Frontal (BA 10)	ns				ns				ns				*	-39	54	5
R Ant Middle Frontal (BA 10)	ns				ns				ns				*	38	54	4
L Thal	ns				ns				ns				***	-11	-19	2
R Thal	ns				ns				ns				***	3	-17	1
L Fusiform (BA 37)	**	-40	-63	-11	ns				ns				*	-43	-63	-14
L Inferior Occipital (BA 18)	**	-26	-87	-15	ns				ns				ns			
R Inferior Occipital (BA 18)	*	18	-90	-15	ns				ns				ns			
R Fusiform (BA 37)	**	39	-52	-21	ns				ns				ns			
M Cb	ns				ns				ns				*	4	-77	-33

ns = not significant, * P < .001, ** P < .0001, *** P < .00001

Table 1: Local maxima of regions activated during quiet working memory trials in Experiment 1.

Table 2
Regions showing significant irrelevant information effects in Experiment 1

	Articulatory Suppression				Irrelevant Speech				Irrelevant Nonspeech			
	e	d1	d2	r	e	d1	d2	r	e	d1	d2	r
Medial Frontal (BA 6/32)	+	+										
L Precentral (BA 6)	+											
Anterior Cingulate (BA 24/32)					-				-			
L Inferior Fr (BA 45/44)	+	+			-		-		-		-	
L Ant Ins (BA 13/45)	+	+			-		-		-		-	
R Ant Ins (BA 13/45)					-							
L Middle Temporal (BA 21)					+							
L Inferior Frontal (BA 44/9)	+				-				-			
L Basal Ganglia (Putamen)			-		-		-		-			

e = encoding, d1 = early delay, d2 = late delay, r = recall

+ Indicates a relative increase compared to quiet working memory trials

- Indicates a relative decrease compared to quiet working memory trials

Table 2: Regions showing significant irrelevant information effects in Experiment 1.

Table 3

Prior studies examining the temporal-specificity of irrelevant information effects

			Effect Size (%E)	
			Encoding	Delay
A. Irrelevant Speech				
Miles et al., 1991	Experiment 1		12.1	15.9
Miles et al., 1991	Experiment 2		2.81	1.17
Miles et al., 1991	Experiment 3		5.6	11.7
Macken et al., 1999			7.99*	8.99*
Tolan & Tehan, 2002	Experiment 1		8.04	23.75
Hanley & Bakopoulou, 2003	Experiment 1		3.51	7.27
MEAN			6.41	11.96
B. Articulatory Supression				
Miles et al., 1991	Experiment 2		11.8	8.19
Miles et al., 1991	Experiment 3		24.07	14.8
MEAN			17.94	11.50

Effect Size (%E) was computed as $\%E = 100((Q-I)/Q)$, where Q is the mean percent accuracy in the quiet condition, and I is the mean percent accuracy under the interference condition (see Logie, Della Sala et al, 1996, see also Neath et al., 2003 for an application of the measure)

* Averaged across two sub-stage conditions

Table 3: Prior studies examining the temporal specificity of irrelevant information effects

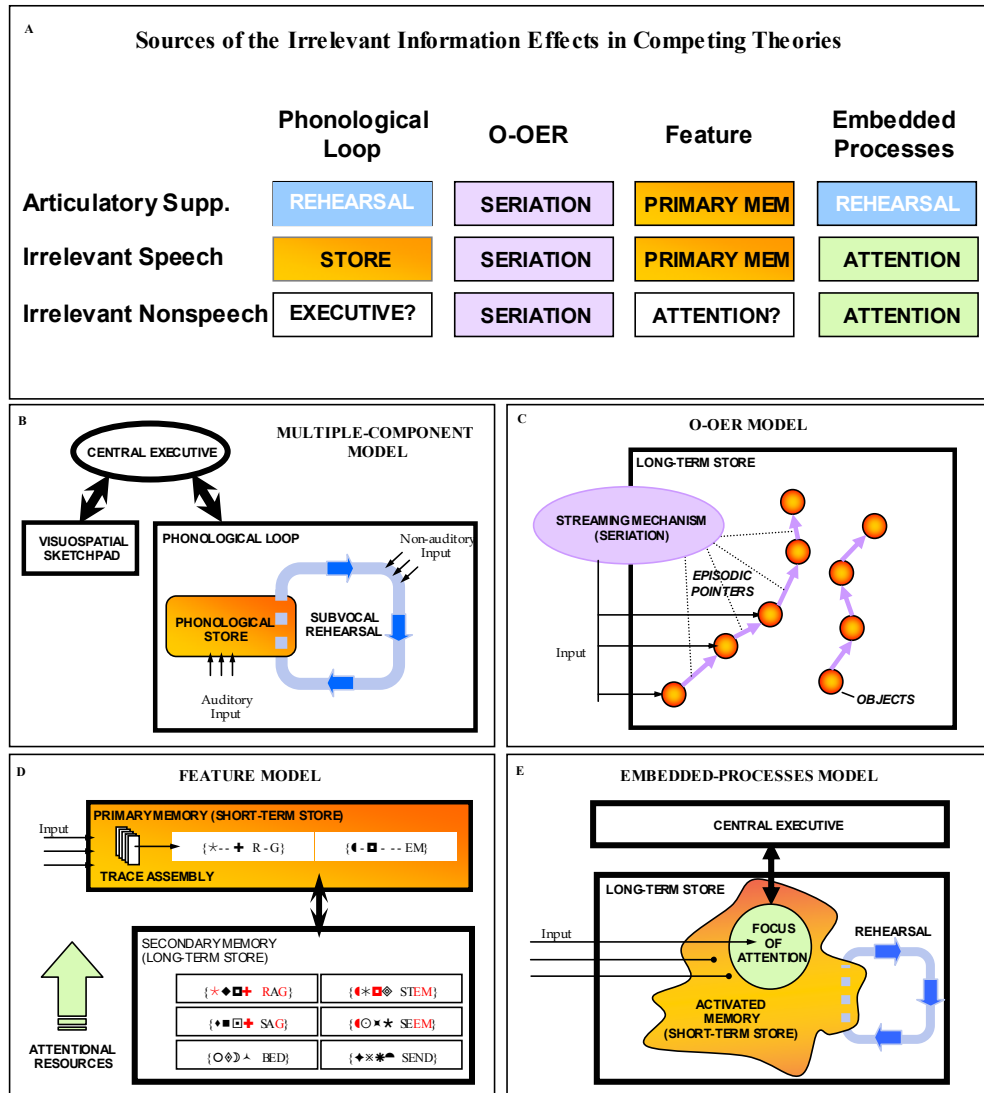


Figure 1: Competing theories of working memory used to explain the irrelevant information effects.

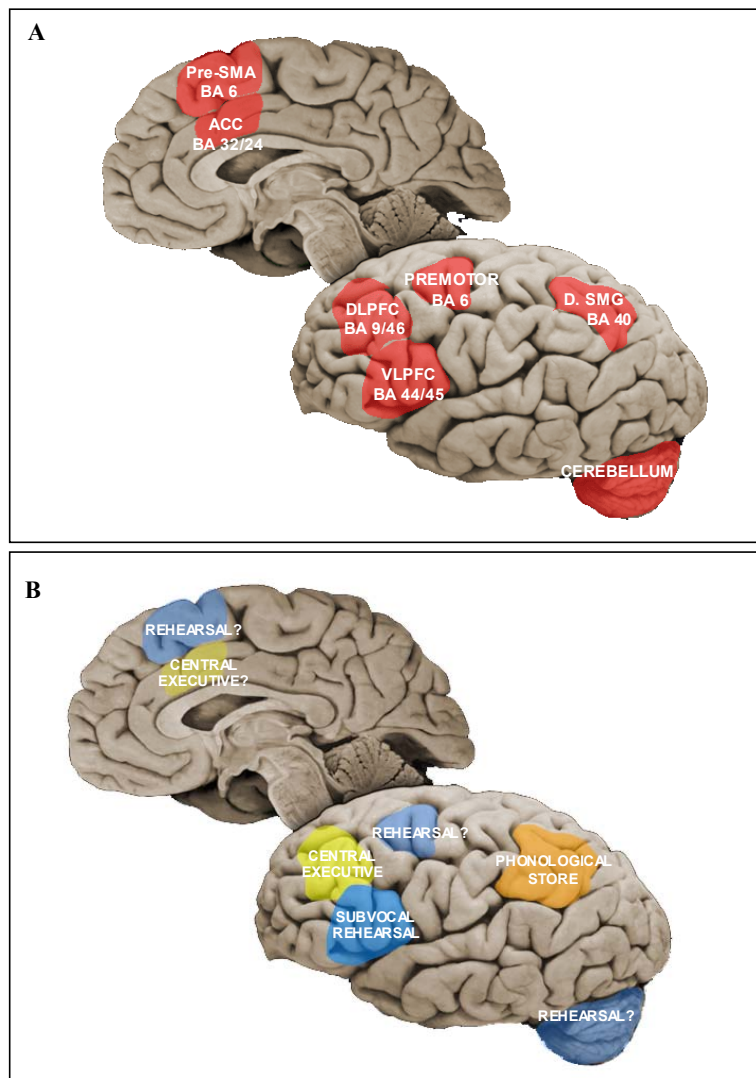


Figure 2: The neuroanatomy of working memory and a mapping of the distribution of function according to the prevailing view

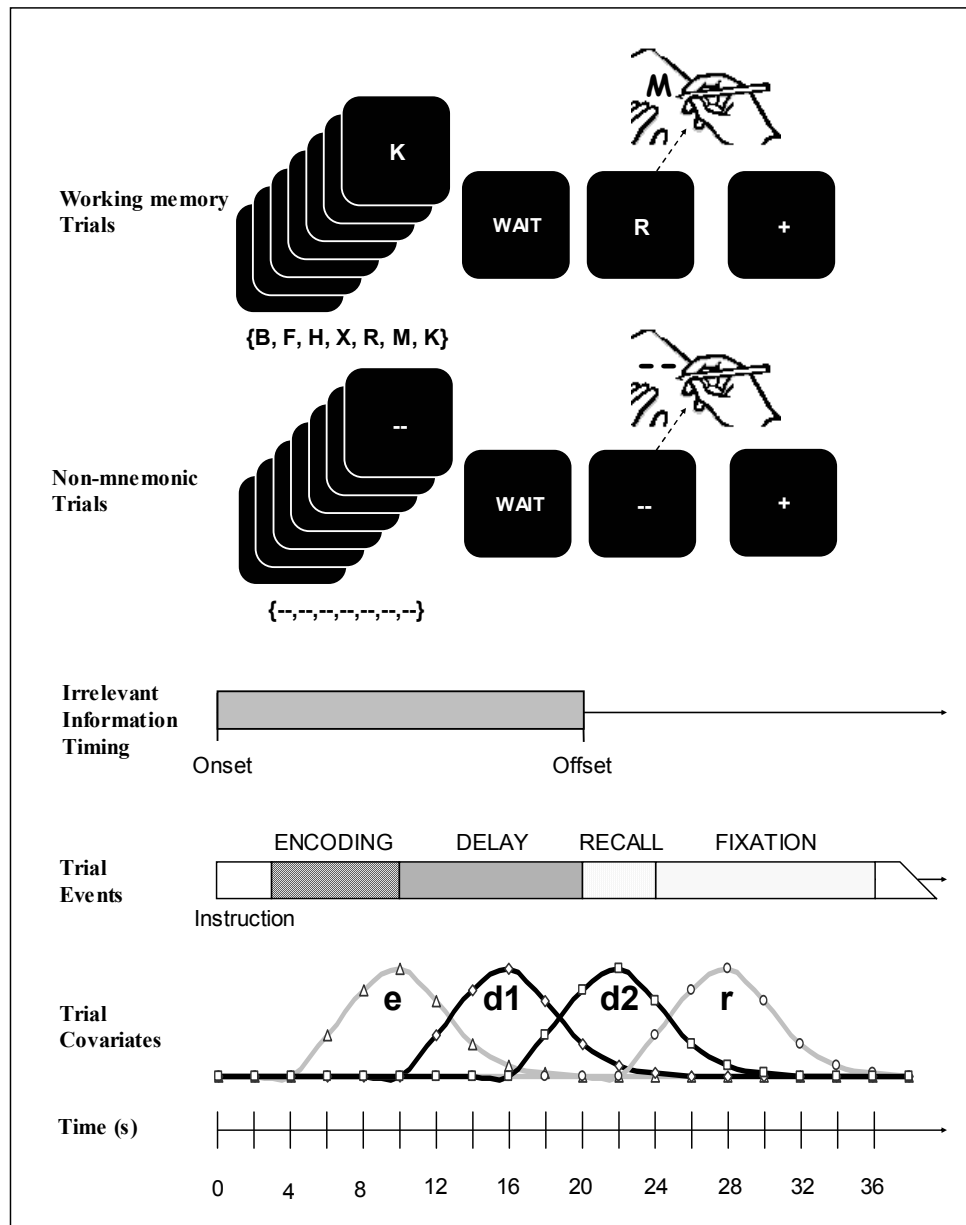


Figure 3: Schematic diagram of the experimental protocol used in Experiment 1.

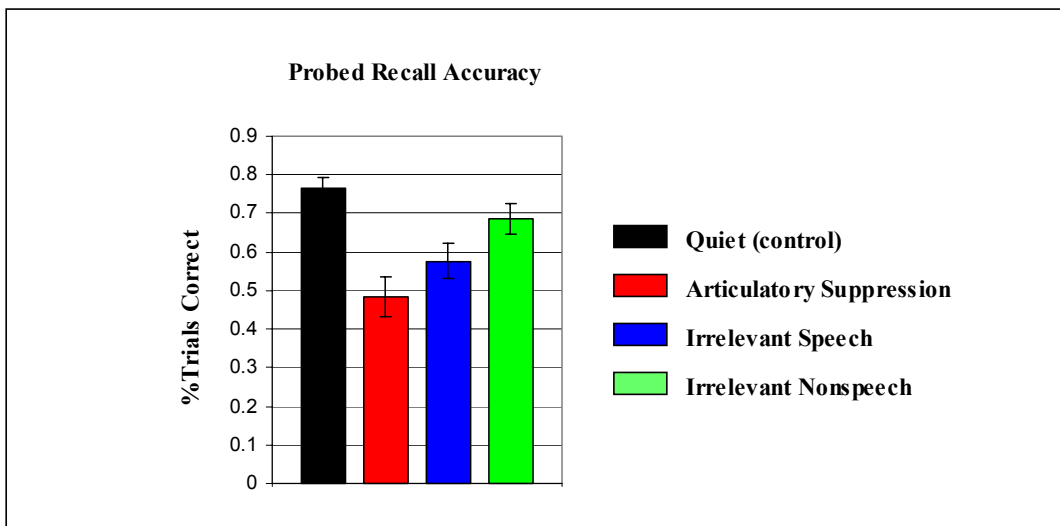


Figure 4: The effects of irrelevant information on probed recall accuracy in Experiment 1.

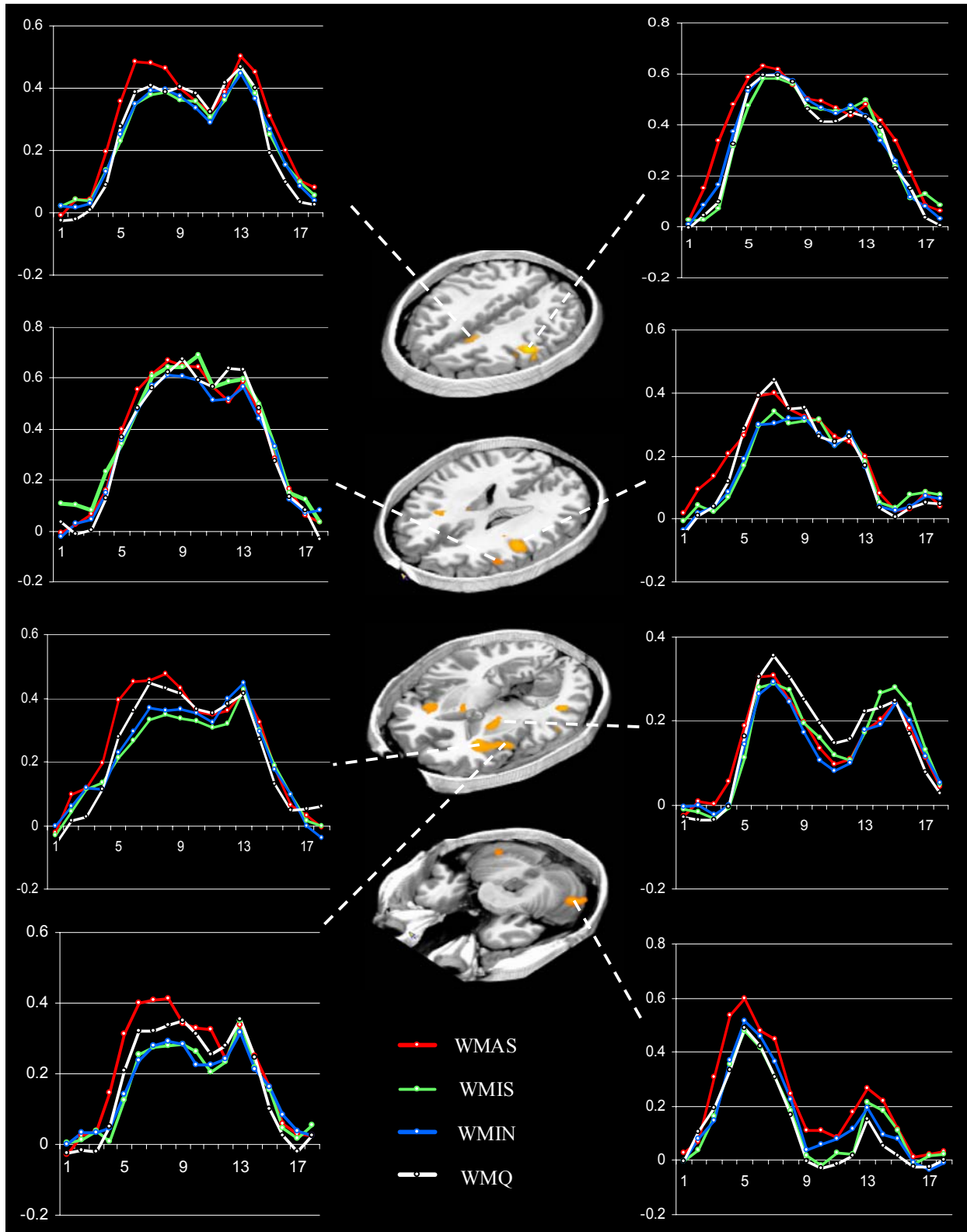


Figure 5: Quiet working memory regions and their activation profiles in Experiment 1.

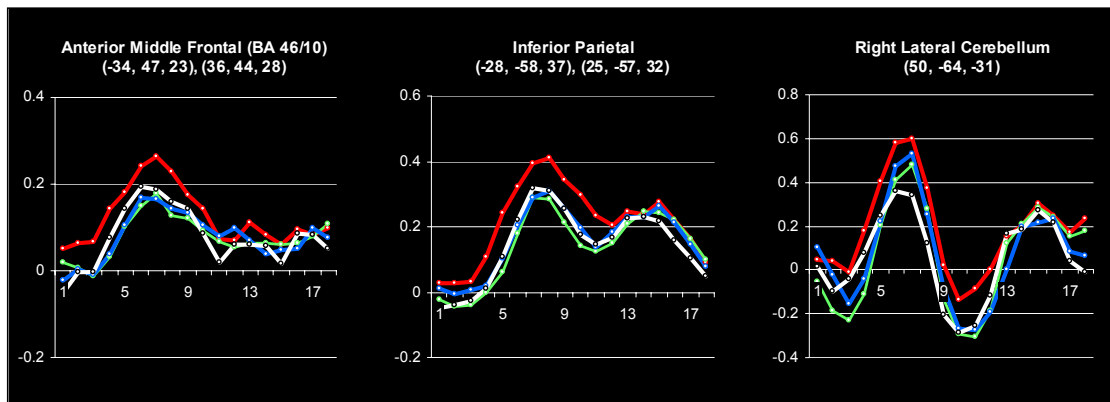


Figure 6: Activation profiles for regions “recruited” by concurrent articulatory suppression trials.

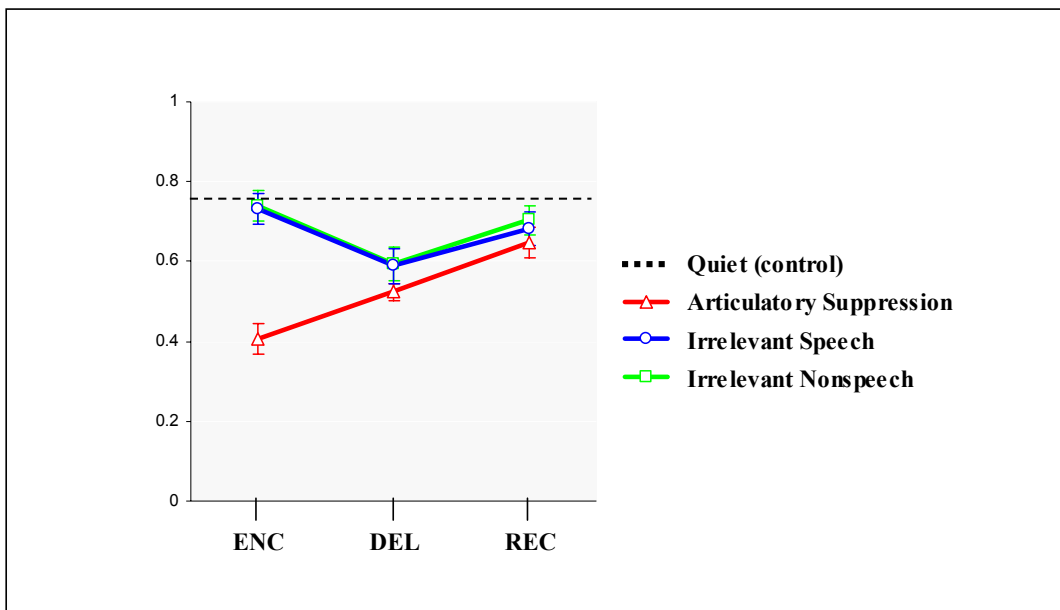


Figure 7: Delayed serial recall task performance under stage-limited irrelevant information in Experiment 2.

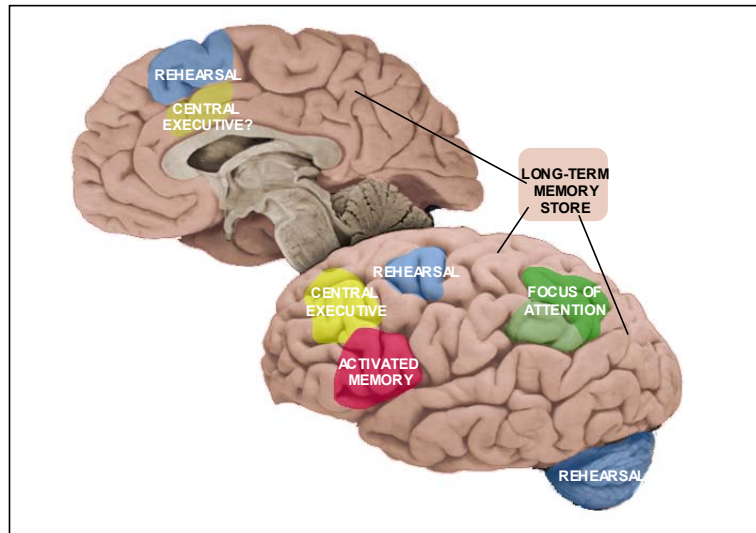


Figure 8: A revised neuroanatomical model of working memory based on the Embedded-Processes Framework.

APPENDIX A

Pilot Studies

Several rounds of behavioral pilot testing were conducted. Initial testing used small subject samples ($n = 6$) to narrow in on an appropriate design and materials. These experiments will not be detailed, but shaped the experimental design of later testing by suggesting that irrelevant sound effects would not be robust unless a post-presentation delay interval was included. These early experiments also yielded particularly weak effects of irrelevant nonspeech with pure frequency tones, leading to the alternative employment of broadband noise stimuli. Two later pilot experiments, reported herein, were completed with larger subject samples.

Pilot Experiment A

The goals of this first full-scale pilot experiment were threefold: 1) to demonstrate significant within-subjects effects of the three irrelevant information types (no published work has examined all three effects within-subjects), 2) to confirm that an articulatory suppression effect could be obtained in the absence of any overt articulatory gestures, and 3) to demonstrate that irrelevant sound effects would persist in the presence of scanner noise. A standard delayed serial recall paradigm was employed.

Participants

Twelve introductory level psychology students from the University of Pittsburgh participated in the experiment in partial fulfillment of a course requirement. All subjects were tested individually, and reported normal hearing and normal, or corrected-to-normal, vision.

Design

The experiment tested delayed serial recall task performance under four irrelevant information conditions: quiet, articulatory suppression, irrelevant speech, and irrelevant nonspeech. Subjects completed ten trials for each condition, with trials sampled by random selection without replacement.

Stimuli

Both the to-be-remembered items and the stimuli used for irrelevant information were identical to those employed in Experiment 1 of the present paper. Sounds were presented to participants through headphones at approximately 70dB (A), as measured by a digital sound level meter (Extech Instruments, Waltham, MA).

Procedure

Each subject participated in a one hour long experimental session in which they performed repeated trials of a delayed serial recall task. After a brief practice period, subjects completed ten blocks of trials. Each block consisted of one trial from each of the experimental conditions. The procedure for each trial was identical to that used in the working memory trial of Experiment 1 up until the end of the delay period, at which point the trial proceeded exactly as in Experiment 2. That is, subject performed the delayed serial recall task under interference that lasted through the presentation and delay periods, and were then prompted to recall each of the seven presented items in their presented order (on the same response sheets as were employed in Experiment 2).

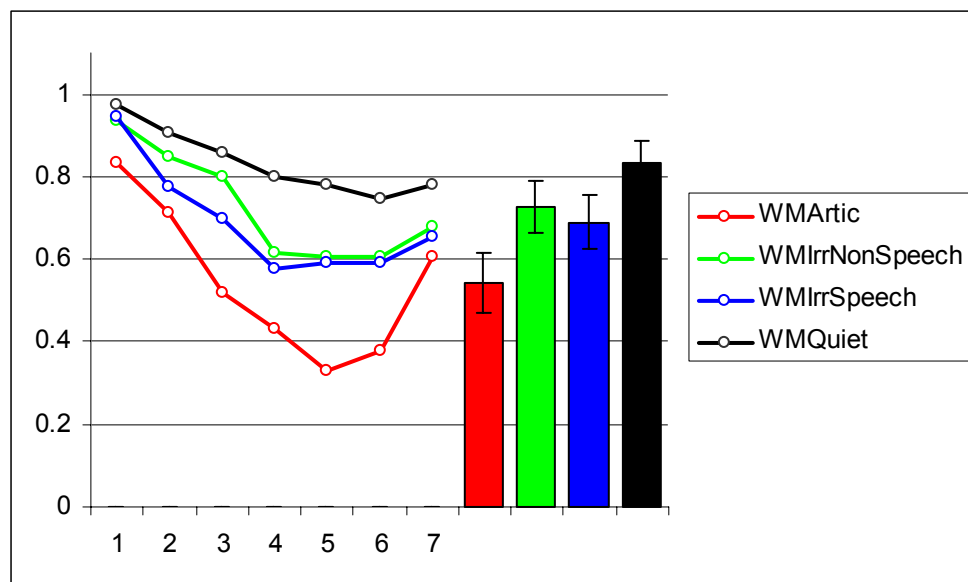
The nature, timing, and instructions regarding irrelevant information were identical to those in Experiment 1. To simulate the scanner environment, a recording of the noise produced

by the functional imaging sequences used in Experiment 1 was played aloud at approximately 95dB throughout the experiment.

Results

Subjects' responses were scored according to a strict serial recall criterion, wherein an item was considered correct only if it was written in the appropriate serial position. Serial position curves and means for each of the experimental conditions are shown below.

Comparisons of each irrelevant information condition to the quiet (control) condition were made to confirm the presence of all three effects. Accordingly, the data revealed significant effects of silent articulatory suppression ($T(11)=5.45$, $p < 0.001$, one-tailed), irrelevant speech ($T(11)=3.50$, $p < 0.01$, one-tailed), and irrelevant nonspeech ($T(19)=2.34$, $p < 0.05$, one-tailed), relative to quiet trials.



Percent of correct responses in delayed serial recall for Pilot Experiment A

Pilot Experiment B

All three goals of the first pilot experiment were met. Specifically, the experiment confirmed that significant irrelevant information effects could be obtained within-subjects, that the articulatory suppression effect remains sizable even when subjects make no overt articulatory movements, and that the irrelevant sound effects persist even in the presence of ambient scanner noise. The second pilot experiment sought to confirm that a probed recall paradigm, as employed in Experiment 1 of the present paper, would yield qualitatively similar effects. This second pilot experiment was identical in every way to that employed in the fMRI study described above (Experiment 1), but took place in a behavioral testing room.

Participants

Twenty two students from the University of Pittsburgh participated in the experiment for monetary compensation. All subjects were tested individually, and reported normal hearing and normal, or corrected-to-normal, vision.

Design

See Experiment 1

Stimuli

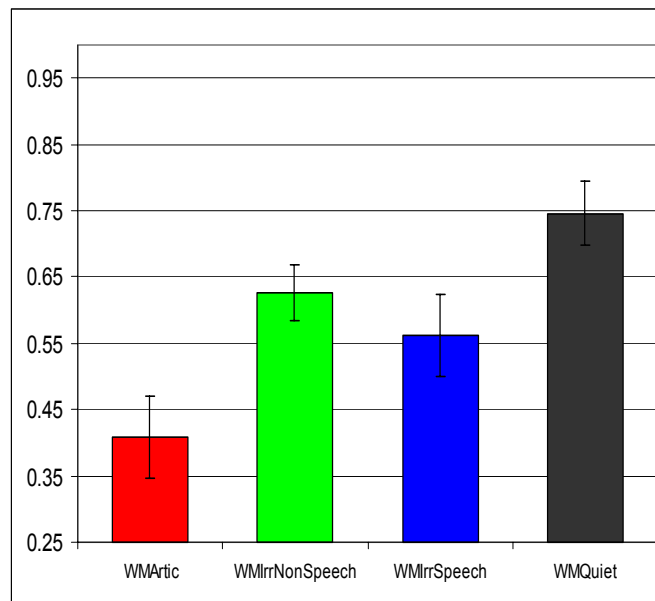
See Experiment 1

Procedure

See Experiment 1

Results

Probed recall task performance was analyzed to characterize the effects of silent articulatory suppression, irrelevant speech, and irrelevant nonspeech. Subject accuracy in each working memory condition was calculated by determining the proportion of trials on which subjects correctly recalled the item that succeeded the probe. The mean accuracy of performance in each condition is shown below. Planned comparisons were used to contrast performance under each of the concurrent processing conditions to that in the quiet condition. Each type of irrelevant information produced a performance decrement, with the proportion of accurate trials under articulatory suppression [mean = 0.41, SD = 0.21, $T(21) = 7.93$, $p < 0.001$, one-tailed], irrelevant speech [mean = 0.56, SD = 0.21, $T(21) = 5.91$, $p < 0.001$, one-tailed], and irrelevant nonspeech [mean = 0.63, SD = 0.15, $T(21) = 3.21$, $p < 0.01$, one-tailed] all significantly reduced relative to quiet (mean = 0.75, SD = 0.17).



Percent trials correct in probed recall task performance for Pilot Experiment B

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